INDEXED

Volume 9 AUGUST, 1939 Number 2

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

« CONTENTS »

The Origin of Stylolites.....*B. M. Shaub* 47

A Modified Logarithmic Probability Graph for the Interpretation of Mechanical Analyses of Sediments.....*George H. Otto* 62

Sedimentary Rocks of the Niagara Gorge.....*John T. Sanford* 77

Reflection of Provenance in Heavy Minerals of the James River.....*Marcellus H. Stow* 86

REVIEWS

Edelman, C. H., Ergebnisse der sedimentpetrologischen Forschung in den Niederlanden und den angrenzenden Gebieten 1932–1937.....*Lincoln Dryden* 92

Journal of Sedimentary Petrology

W. H. TWENHOFEL, EDITOR
Madison, Wisconsin

ASSOCIATE EDITORS

MARCUS A. HANNA
Houston, Texas

U. S. GRANT
Los Angeles, California

W. C. KRUMBEIN
Chicago, Illinois

CLARENCE S. ROSS
Washington, D.C.

HENRY B. MILNER
London, England

R. DANA RUSSELL
University, Louisiana

The JOURNAL OF SEDIMENTARY PETROLOGY is published by the Society of Economic Paleontologists and Mineralogists, a division of The American Association of Petroleum Geologists. Numbers are issued in April, August and December.

The subscription price of the JOURNAL OF SEDIMENTARY PETROLOGY is $3.00 per year prepaid to addresses in the United States, Mexico, Cuba, Porto Rico, Panama Canal Zone, Republic of Panama, Dominican Republic, El Salvador, Bolivia, Colombia, Honduras, Nicaragua, Peru, Hawaiian Islands, Philippine Islands, Guam, Samoan Islands.

Single numbers, $1.50 each.

Postage is charged extra: For Canada, 20 cents on annual subscriptions (total $3.20), and for all other countries in the Postal Union, 40 cents on annual subscriptions (total $3.40).

The JOURNAL will furnish reprints at cost. Orders should accompany corrected galley proof.

Communications about the JOURNAL, subscriptions, rates, memberships, change of address, advertising and non-receipt of preceding numbers should be addressed to Society of Economic Paleontologists and Mineralogists, P. O. Box 979, Tulsa, Oklahoma. Claims for non-receipt of preceding numbers must be sent in within three months of the date of publication in order to be filled gratis.

Communications in regard to manuscripts or purely editorial matters should be addressed to W. H. Twenhofel, Editor, University of Wisconsin, Madison, Wisconsin.

GEORGE BANTA PUBLISHING COMPANY, MENASHA, WISCONSIN, U.S.A.

Volume 9 AUGUST, 1939 Number 2

Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

CONTENTS

The Origin of Stylolites.....*B. M. Shaub* 47

A Modified Logarithmic Probability Graph for the Interpretation of Mechanical Analyses of Sediments.....*George H. Otto* 62

Sedimentary Rocks of the Niagara Gorge.....*John T. Sanford* 77

Reflection of Provenance in Heavy Minerals of the James River.....*Marcellus H. Stow* 86

REVIEWS

Edelman, C. H., Ergebnisse der sedimentpetrologischen Forschung in den Niederlanden und den angrenzenden Gebieten 1932–1937.....*Lincoln Dryden* 92

NOTICE

Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

Persons who are not members of the Society of Economic Paleontologists and Mineralogists or are not subscribers to the *Journal of Sedimentary Petrology* but who desire to publish an article in the *Journal*, should have some member of the Society of Economic Paleontologists and Mineralogists or some member of the American Association of Petroleum Geologists sponsor the article. Members of these Societies are given preference in publication.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 9, NO. 2, PP. 47–61, FIGS. 1–9, AUGUST, 1939

THE ORIGIN OF STYLOLITES

B. M. SHAUB
Smith College
Northampton, Massachusetts

ABSTRACT

An examination of the generally accepted theory of origin for stylolites has been made, first, on theoretical grounds and, second by applying it to observed features and relationships of stylolites occurring in the limestones of southern Indiana and the dolomitic limestones and dolomites at Lockport, N. Y. The solution theory not only fails to meet the theoretical requirements but likewise fails to account for many structures and relationships associated with stylolites. The contraction-pressure theory which has been advanced to explain the origin of type 2 (22–338) of cone-in-cone structures has been applied, with modifications, to the origin of stylolites. The occurrence of stylolites in sandstone and quartzite, as well as in the carbonate rocks, is readily accounted for by the contraction-pressure theory, which also explains the wide variation in form, structure, markings and other features of stylolites. A new marking found on stylolite columns at the Lockport locality supplies critical evidence supporting the contraction-pressure theory vs. the solution-pressure theory. The new marking is described as adhesion ridges.

INTRODUCTION

Stylolites, structural features occurring chiefly in limestones, dolomites, marbles, and very rarely in sandstones (1) and quartzites (2), have been discussed in the literature since 1751, when they were first described by Mylius as "schwielen" and were compared with petrified wood. In 1828, Klöden (3) named the structure "Stylolithes sulcatus" as he considered it to be a distinct organic species. Numerous theories have been advanced for the origin of this conspicuous and intricate suturing or interpenetration of the adjacent parts of the same or adjoining beds. The theories may be enumerated as follows: *a*, organic theory (4); *b*, crystallization theory (5); *c*, erosion theory (6); *d*, gas theory (7); *e*, bitumen theory (8); *f*, pressure theory (9); and *g*, solution-pressure theory (10).

In 1922, Stockdale (11) published a comprehensive paper on the nature and origin of stylolites, in which he gave an excellent resumé of the previous theories and descriptions of the stylolites from the limestone areas of southern Indiana. He also included a bibliography of 88 titles on stylolites and related subjects. While he is not the originator of the solution-pressure theory, Stockdale presented evidence to substantiate the theory that stylolites are formed by differential solution in hard rock as a result of an initial differential solubility of the rock.

AN EXAMINATION OF THE SOLUTION-PRESSURE THEORY

Stockdale, in 1922, (11–46) wrote:

> Stylolite phenomena result from differential chemical solution in hardened rock, under pressure, on the two sides of a bedding plane, lamination plane, or crevice, the individual portions of the one side fitting into the dissolved-out parts of the opposite, the interfitting taking place slowly and gradually as solution continues. Stylolites are limited to carbonate rocks.

Six years prior (1916), Tarr (2) described the occurrence of stylolites in quartzite, a material extremely insoluble to any of the natural solvents contained in ground water.

The solution-pressure theory is based principally upon the following physico-chemical phenomena (11–49):

1. "The effect of pressure upon the solubility of solids."
2. "The differential solubility of limestone and other carbonate rocks."

If one examines Stockdale's illustration of a differentially soluble limestone (11—Fig. 19), he will find it to be a specimen channeled by small water courses and to show a "differential solubility" varying from one lamination to another, as is indicated by the projections of numerous laminae as fins or blades. In limestone areas, similar examples of channeling are abundant and are characteristically represented on a larger scale by the common limestone pinnacles. Channeling of this kind does not appear to be due to a "differential solubility" between the material formerly occupying the channels and the now-remaining walls. The channels seem to have originated as the result of the original unevenness of the limestone bed when first exposed to the movement of ground water, together with the controlling influence of the overlying weathered material which, on account of its variable permeability, would exert a guiding influence upon the movement of subsurface drainage. The limestone beneath permeable zones of the overlying, unconsolidated material and that along joint and fracture planes where the subsurface drainage is able to move freely would be expected to yield to solution far more readily than under areas of stagnant water. The development of channels and accompanying pinnacles is too obviously associated with sub-surface drainage to use the phenomenon of channeling as a basis for postulating horizontal variations in the solubility of the limestone corresponding to the plans of the channels.

In considering a limestone as having a "differential solubility," one may be confusing the term with the *rate of solution* or the *ease of solution*. The chief soluble constituent of a limestone is calcite and, as the solubility of calcite depends upon the nature of the solvent or solution phase instead of the solid phase, the amount of calcite dissolved from any limestone per unit volume of solvent will, in time, be the same when equilibrium is established.

The impurities in limestones are dominantly clay minerals and some colloidal silica, together with variable amounts of organic matter. These are usually deposited with the lime ooze as very fine-grained particles, and probably much of this material approaches colloidal proportions. Such impurities would be rather uniformly distributed horizontally throughout the depositing water. Hence it would hardly be expected that the clay and other impurities would be irregularly deposited with sharp boundaries in a horizontal direction and arranged according to the plans of existing channel systems or stylolite seams.

In 1926, Stockdale illustrated diagrammatically (12—Fig. 1) his conception of the conditions before and during the development of stylolites according to the solution-pressure theory. In Stockdale's ideal diagram, reproduced in Fig. 1, he has assumed that the long dimensions of the "slightly less resisting portions of the rock" are perpendicular to the bedding; i.e., the direction of least resistance to solution is shown to cross the planes of stratification, in which direction one should naturally expect the greatest variation in the rate or ease of solubility.

The *rate* of solubility contains a time factor and one may readily contend that geologic time is so long that the solution of the more resistant layers may progress very slowly and still develop stylolites 15 to 18 inches long. The solution-pressure theory requires that the points of the columns are more resistant than the "parts to be removed by solution"; nevertheless, with abundant time, the points would also succumb to solution in the same manner as the other resistant parts of the limestone.

One may observe from Stockdale's diagram and his description of it, Fig. 1, that in order for stylolites to develop according to the solution-pressure theory, the natural processes of deposition would have to deposit systematically on the opposite sides of the "bedding plane, lamination plane or crevice" a sharply

bounded pattern of "differentially soluble" limestone in such a manner that the more and the less resistant parts stand opposite each other in order that stylolites start their development at some geologically later date. It is, indeed, difficult to understand how sedimentary processes could deposit such very fine-grained materials (or how later processes could rework them) so as to produce such a sharply defined arrangement of more and less soluble material. Other, and more highly improbable conditions of deposition, or later reworking, are required to produce the necessary relationships to initiate the development of stylolites along crevices, faults and especially along unconformities. Such a definite prearrangement of materials constitutes the most basic requirement of the solution theory. As the foregoing assumption concerning the arrangement of differentially soluble materials does not appear to be a valid one, the solution-pressure theory, as described by Stockdale, appears to the writer to be based upon premises that are fundamentally unsound.

According to the principle that increased pressure increases the solubility of certain solids, it is possible to define a *pressure-solution* theory* for the origin of stylolites by assuming that differential solution of the limestones along permeable bedding planes, lamination planes, etc., would be initiated as the result of differentially applied pressure; and that the process of solution would be continued by variations in the intensity of the pressure on adjoining areas. A serious objection would at once confront a *pressure-solution* theory. As lime oozes and other calcareous sediments are sufficiently plastic to flow very readily whenever and wherever a slight difference in pressure develops, it is difficult to see how high differential pressures, having intensity patterns like the cross-sections of stylolite columns and stylolite seams parallel to the bedding, could exist at the time when the sediments became solid. The writer cannot find a physical or chemical basis for believing that such

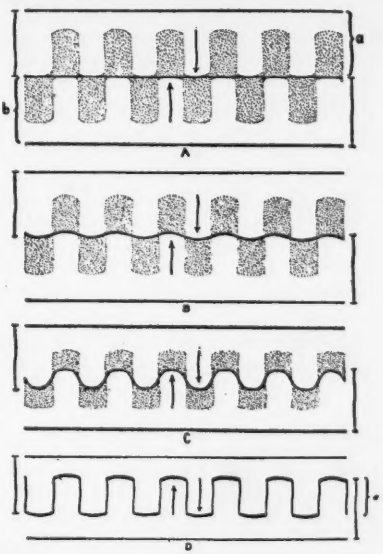

FIG. 1.—Stockdale uses this diagram (12—Fig. 1) in describing the origin of stylolites according to the solution-pressure theory. His description follows: "Diagram illustrating the development of stylolites from an ideal situation. The dotted areas are those to be removed by solution, representing slightly less resistant portions of the rock. In *A*, no solution has taken place. The limestone beds, *a* and *b*, are separated by an even bedding plane. A slight amount of solution has taken place in *B*, producing an undulating seam. Greater solution has taken place at the stage *C*, giving more pronounced undulations. Pressure is the greatest at the crests and troughs of the undulations. A final development of columns is shown in *D*. A dark residue remains at the end of each column. The amount of thinning is indicated by *e*."

* The writer has not encountered a description of such a theory, although it may exist in the scattered literature on stylolites. Such a theory would eliminate the basic assumption of the solution-pressure theory that the limestones are "differentially soluble" parallel to the bedding. In general, any objection to either theory would also apply to the other. The basic assumption that a differential pressure could exist that would initiate the development of stylolites is also open to serious objections as stated below.

a system of variable pressures could develop and repeatedly re-develop over areas of stylolitic proportions, after the rock is consolidated. We may, however, in support of either theory, assume that differential pressures, having intricate patterns, could exist at the time the limestone became hard and that solution would be possible about the points of greatest pressure. Immediately upon the removal of a very small fraction of an inch, the increased pressure would be released and the result would be an equalization of the pressures over the area affected. Solution would then cease and the amount of limestone removed would be too small for visual detection. For the process to operate continuously, there would have to be a constant rejuvenation of the identical pressure pattern. It is difficult to conceive of any physical or chemical conditions which would repeatedly re-establish such a set of differential pressures in solid materials having the physical properties of a consolidated limestone, dolomite, marble, sandstone or quartzite.

ADDITIONAL OBJECTIONS TO ANY THEORY INVOLVING EXTENSIVE SOLUTION ALONG STYLOLITE SEAMS

The pronounced solution in limestones, at or near the surface, which results in the development of channels, pinnacles, karst topography, or the formation of caves, appears to have no bearing on, or genetic relation to, the origin of stylolites. The above-mentioned unquestionable and obvious solution structures are directly associated with ground water in *motion*, and owe their origin to some form of "break," i.e., joints (13—Fig. 3) or other structures, along which ground waters having sufficient hydraulic gradient may move; at first, very slowly when the breaks are narrow and offer high resistance to flow. Such surface solution-structures are in juxtaposition with stylolite seams only because the rocks which *already contain stylolite seams* are gradually subjected to the downward encroachment of the ground water channels as the surface materials are eroded. There is a striking discontinuity between these surface or near-surface solution effects and stylolite seams and columns.

Among the many additional objections to extensive solution below flowing ground water channels by percolating water as along stylolite seams or along bedding planes, one may consider the following:

1. The first difficulty to be encountered in tracing the downward and lateral movement of water through the shales and limestones is the fact that these two kinds of rock usually offer very effective barriers to the passage of water, oil, and even natural gas, although these substances may be under very high pressures.

2. Shafts and drifts in *unbroken* rocks near the surface are relatively dry unless the penetrated rocks are permeable like partially cemented sandstones. Even water-bearing joints and other water-carrying fractures decrease rapidly with depth, so that the quantity of water percolating through shales and carbonate rocks must be very small below the lowest ground water channels.

3. Reference has been made to estimates that, in some instances, as much as 40 to 50 per cent (12–406) of the original limestone strata along stylolite seams and bedding planes was removed by solution during the formation of stylolites.

At the rate of 0.191 grams of calcium carbonate being soluble in one liter of sea water (14–108), a depth of water equivalent to more than 20 miles would be required to remove the material dissolved from stylolitic formations for every ten feet of material (calcite) removed—i.e., providing the sea or surface water contained no calcium carbonate at the start and reached the locations of the stylolite seams or bedding planes without dissolving any calcite while it was slowly percolating through the overlying rocks, many of which would certainly be rich in calcium carbonate. In numerous stylolite formations the combined or total

penetration of all of the stylolite columns and seams is several times ten feet which would require an extraordinary amount of water to remove the material in solution.

4. As there are no channels, joints or other open fractures directly associated with stylolite seams, the water must move in capillary films through the overlying rock; consequently, it would be expected that the water would become saturated from the *prolonged* contact with the calcareous portions of the overlying sediments at every horizon where the calcium carbonate content of the rock is important. Hence, the downward percolating water, which would undoubtedly have been in intimate contact with many "less resistant parts" of the limestone, would, in all probability, be saturated when it reached the seam along which the differential solution is supposed to have occurred. The removal of calcite in solution from the overlying strata would leave them in a highly porous condition, which is contrary to the observed facts. A uniform porosity could not develop, for there would be zones where the pores would coalesce and channels would result. Such channels related to stylolite seams are apparently absent.

5. The ever-present and conspicuous striations parallel to the length of the columns militates against an origin by solution. Such regular, parallel and uniform configuration of striae is a feature that is unknown, in a heterogeneous material, where undoubted solution processes have been active and where the known differential rate of solution is at right angles to the striations. Similar striations are common to all processes extruding plastic substances.

6. The origin of stylolites in sandstones and quartzites, extremely insoluble rocks, likewise militates against an origin according to the solution theory.

In commenting upon the origin of stylolites in quartzite in conformity with the solution-pressure theory, Twenhofel (15) states that, due to the insoluble nature of quartzite, "other and yet unknown factors may form structures similar to the stylolites of limestones and dolomites."

A REVIEW OF THE IMPORTANT PHYSICAL PROPERTIES OF THE FINE GRAINED SEDIMENTS

Any theory developed to apply to the prominent and conspicuous structures in undisturbed sedimentary rocks, and to some extent in metamorphic rocks, should not overlook the common origin of all sediments from detrital and chemically precipitated materials, together with the common properties of these substances before and during consolidation. Two properties of all finer-grained sediments are a state of high porosity and the ability to assume more than one state of packing upon deposition. Another very important property is that of plasticity (16). Ries (17–165) defines plasticity as "the property which many bodies possess of changing form under pressure, without rupturing, which form they retain when the pressure ceases, it being understood that the amount of pressure required, and the degree of deformation possible, will vary with the material." This definition can be applied to permanent deformations in all kinds of materials, but in the following discussion *only those materials in which the modulus of elasticity, elastic deformation or the ratio of stress to elastic strain, over a comparatively short period of time, is very low, or practically nil, under normal conditions of temperature and pressure as associated with unconsolidated sediments, will be referred to as being plastic.* The cause of plasticity in the very fine-grained sediments is not thoroughly understood (17–165), but it is believed to be due in a greater or less degree to one or more of the following states and properties of clay, and one or more of these may equally well apply to other fine-grained sediments: plate structure of particles, fineness of grain, molecular attraction, adsorption, soluble salts, bac-

teria, organic matter, high surface tension and colloids.

Plasticity varies from one kind of sedimentary material to another and also between materials of apparently the same kind. It also varies greatly with the water content and is destroyed upon complete loss of water. The more plastic clays usually have a higher degree of hardness or cohesion after the removal of the pore water (17–167). Another fundamental and important property of fine-grained sediments is that of volume contraction accompanying the process of dewatering.

In discussing the physical properties of clays, Bleininger (18) states that "immediately upon the molding of plastic clay evaporation of water begins which is accompanied by a shrinkage in volume. The shrinkage is exactly equal to the volume of water lost, down to the point at which further contraction ceases. The most plastic clays also show the greatest contraction. According to the nature of the clay the contraction may be from 10 to 35 per cent in terms of the original, wet volume."

Lateral contraction is a very prominent feature of fine-grained terrestrial sediments of aqueous origin during the dewatering process by evaporation. The obvious result is the development of prominent mud cracks, which produce a considerable *lateral displacement* of materials with little or no distortion of the material unless it is laminated and varies greatly in texture.

In describing the cracks in the calcareous muds near Miami beach, Florida, Kindle (19–140) states that "over most of the area the polygons were from 6 to 15 inches in diameter, with cracks separating them which were mostly from 2½ to 3 inches wide. . . ." By averaging these figures one obtains a horizontal shrinkage of 20.75 per cent, which gives a very approximate figure for this value. If we assume that the value of the vertical shrinkage or compaction is ⅓ the horizontal value, when there are no overlying deposits, the volume shrinkage is of the order of 43 per cent. These approximate values, as well as the excellent illustrations figured by Kindle, are quite convincing in showing that calcareous muds possess the property of volume contraction to a very high degree upon the removal of pore and adsorbed water.

The general and widespread association of stylolite columns and seams with bedding and lamination planes indicates an especially close genetic relationship with these structures. As stylolites are rarely associated with faults and crevices there must be one or more features common to bedding planes, certain fault planes and crevices in so far as the origin of stylolites is concerned.

The early stages of the compaction of the fine-grained sediments are marked by a decrease in porosity, which is accomplished by a downward movement of the sediments through the water (20). When the porosity is greatly reduced, the remaining open spaces become more and more contracted so that the continued reduction in porosity is accomplished by the upward movement of water through the capillary openings, which offer less resistance in this direction than laterally, unless acted upon by some external forces.

In the above brief review of the physical properties of fine-grained sediments the important property of shrinkage or volume contraction has been discussed, and its importance during the dewatering of sediments has been emphasized. The writer wishes to point out that he does *not* believe that the horizontal tension stresses in subterranean sediments due to volume contraction, associated with the dewatering of the sediments, even remotely approach the magnitude necessary to produce open cracks. He does, however, believe that a definite and important horizontal component due to volume contraction does, at times, exist and that its magnitude is sufficient to produce areas of *differential horizontal* stresses which will be continually rejuvenated during dewatering of the sediments.

If low continued stresses can cause permanent deformation in hard, rigid bodies, it must be obvious that very low continued stress will cause considerable movement or plastic flow of such soft materials as clay and lime ooze.

CONTRACTION-PRESSURE THEORY FOR ORIGIN OF STYLOLITES

The lack of definite quantitative data concerning the properties of fine-grained materials during compaction leaves much to be desired in the problem of stylolite genesis. Until more accurate and specific data are available, the following tentative outline is given to present some of the probable phases of the contraction-pressure theory to account for the development of stylolite seams and columns.

1. During the process of compaction the interbedded clay bands become less permeable to water than the lime oozes and offer an increased resistance or retarding action to the upward movement of pore water.

2. The restraining action of the clay causes the pore water to accumulate in the lime ooze beneath the clay partings, thus keeping it in a more highly plastic condition, providing the particular lime ooze possesses the property of high plasticity.

3. The lime layer immediately above a clay layer or parting will become less porous and plastic, with increasing volume contraction as the pore water moves upward to the under side of a higher clay layer that is relatively more impervious; or if unobstructed, it will continue to move upward into the more porous parts of the later sediments.

4. The removal of the pore water causes the lime particles to draw together laterally as well as vertically. The lateral contraction produces horizontal tensile stresses. While these are probably not very high, nevertheless, when superimposed upon the horizontal compression stresses due to compaction, differential horizontal stresses result. The greater the volume contraction the greater the differential stresses may become. As resistance to plastic flow in lime oozes and similar materials is probably rather low, very small stresses in these substances will produce relative motion between the differentially stressed portions. Consequently differential pressures of appreciable magnitude could not develop.

5. The proximity of plastic material on one side of a soft clay band and less plastic material under differential horizontal stresses on the opposite side establishes conditions where the more plastic material will flow into the places where the pressure is reduced. The process of compaction is under gravitational control, hence the normal direction of the transfer of material by plastic flow will be approximately at right angles to the bedding. Where the more and less plastic materials are strongly influenced by dynamic forces, the flow may be in any direction.

6. At the beginning of plastic flow from one side of a clay band to the other, the clay is sheared and carried ahead of the penetrating plastic material. The motion between the parts on the opposite sides of the clay band is relative, hence the beds are mutually and simultaneously penetrated by material moving from the one to the other.

7. The transfer of material by plastic flow under very low differential pressure between the adjoining beds is believed to be slow, orderly and usually non-turbulent. The transfer is accomplished in such a manner that little evidence of dragging is developed, except at the contacts. This is believed to be due, in part, to the contracting action which assists in pulling the material laterally by the cohesive action between the particles as the pore water is removed.

8. The gradual removal of pore water, and consequent gradual and continued volume contraction provide the necessary differential stresses for a prolonged transfer of material, which will continue until the stress differences become too low to overcome the resistance to plastic flow.

9. There appears to be no valid reason

why, under certain conditions in limited areas, the more plastic material may not be above a bed in which differential stresses may develop. Such a condition may arise from the physical characters of the materials of the adjoining beds.

10. As uniformity is much in the minority in nature, one would expect an uneven distribution of the differential stresses caused by volume contraction. An excellent example is the ramifications of mud cracks. One must remember, however, that the terrestrial muds are in an entirely different environment by having one surface in direct contact with the atmosphere, which causes a very high rate of dewatering by evaporation and consequently rapid volume contraction in the surface portions.

The occurrence of stylolite columns and seams observed by the writer or described by other investigators, can be, in all cases, explained by the tentative outline of the contraction-pressure theory given above. Its application to the following general occurrences of stylolite columns and seams should be noted:

1. The more impervious the clay seam, and the greater its areal extent, the greater will be the accumulation of pore water beneath it and, therefore, a greater thickness of plastic material will be available to move into the areas or zones of differential horizontal pressure in the base of the overlying stratum; thus accounting for the more extensive and prominent seams as well as for the larger columns being associated with thicker clay caps.

2. Thin seams of clay offer relatively less resistance to the upward movement of water than thick seams, and therefore the variation in the water content on the opposite sides of the thin seams does not differ enough to set up the necessary pressure differences by contraction or shrinkage to cause extensive plastic flow; hence the columns and seams will be relatively small.

3. As all clay seams are lenticular and thin out at the peripheries, we have, according to the principles of the contraction-pressure theory, a complete answer to the fading out of stylolite seams into the surrounding limestone and to the occurrence of thicker clay caps over the prominent parts of the seams.

4. The development of stylolites along any other structural planes, as crevices and faults, is believed to be due to the physical conditions of the materials along these planes. The materials bordering the planes have probably been affected by the shearing action which rendered them more resistant to the free transfer of pore water from one side to the other. Any thin bed which retards the movement of pore water can function in the same manner as an interbedded clay seam during the formation of stylolites. The pore water which comes in contact with the stylolite seams developed along crevices and faults may supply in colloidal form all the visible clay observed in such instances.

5. Stylolites in sandstones and in quartzite are believed to originate in the same manner and for the same reasons as outlined above for their origin in lime oozes.

SOME STRUCTURAL FEATURES ASSOCIATED WITH CLAY CAPS

The occurrence of clay along the sides and especially at the extremities of the stylolite columns has been frequently described. Stockdale (11–83) states that the "thickness of the clay caps is always directly proportional to the length of the stylolites" projecting into any given bed. This statement does not agree with the observations of the writer, for there are many short columns that are covered by, or rest upon, a layer of clay which is at least equal to, or greater in thickness than, those associated with the nearby columns three or four times their length (Fig. 2). There is, however, a striking uniformity of the thickness of the clay caps associated with any given seam for a considerable length along the seam; nevertheless, with the decrease in strength of the stylolite seam, the clay caps diminish in thickness and dis-

appear or continue as a very thin seam. The clay caps may, in places, uniformly cover the ends of stylolite columns while in other instances the clay caps show an unmistakable bending about the point of the column and a pronounced drag in the clay along the sides, as well as a distinct bending of the laminae beneath the clay cap, all of these clearly indicate movement while the material was plastic instead of phenomena associated with solution.

OBSERVATIONS ON THE RELATIONSHIPS BETWEEN FOSSILS AND STYLOLITE SEAMS

The fossils in the limestones near stylolites are nearly always broken and either abraded or corroded. The extent to which abrasion and corrosion work independently or in conjunction is probably beyond accurate investigation.

According to the contraction-pressure theory the corroded fossils as well as others deposited in the clay seams and the adjoining material, would be carried along ahead of or within the column. In this position their corroded appearance may be erroneously interpreted as due to the effects of solution accompanying the development of the stylolite, as postulated by the solution theory. The fossils which terminate the short columns are corroded apparently to the same extent as those terminating the longest ones. This relationship suggests that the fossils were attacked prior to the development of the stylolites.

The *apparent* penetration of fossils by stylolites has been used as conclusive evidence that stylolites originate according to the principles of the solution theory. Stockdale concludes that the apparent penetration of fossils by stylolites "alone precludes all other theories of the origin of stylolites" (11–64). Consequently, during the examination of the stylolite occurrences in Indiana and at Lockport, N. Y., special effort was made to determine accurately the relationship of fossils to stylolites. The apparent penetration of fossils by stylolites can be readily explained on the basis of the relative shearing strengths of the various shells and the unconsolidated lime ooze. The cross-sectional area of a stylolite column may be controlled wholly or in part by the outline of the shell when the shearing strength of the shell is greater than that of the surrounding material involved in, and adjacent to, the stylolite at the beginning of its formation. When the shells are of paper thinness and possess relatively low resistance to shearing they are cut and carried, in part, along with the stylolite column. The several parts of the sheared fossil take the cross-sectional outline of the periphery of the column. In some of the stylolites there is abundant evidence of motion in the material, as the larger fossils are often standing on end (Fig. 3), a position which they would not assume as the result of sedimentation.

The rather frequent occurrence of calcite or other minerals between stylolite columns and their walls has invited the suggestion that the spaces occupied by the minerals were also formed by solution accompanying the development of the stylolite columns or seams according to the solution theory. That this may not be the case is shown by the relationship of the stylolite seam of Fig. 4 in which the continuation of a stylolite seam is joined by a plastic shear plane which carries the characteristic drag striae on each wall and the striae on both walls are covered by well developed and terminated calcite crystals. The open space formed along this plastic shear plane indicates that continued contraction of the lime ooze pulled the two sides apart at a time when the material was firm enough to hold its shape.

MARKINGS AND STRUCTURES ASSOCIATED WITH STYLOLITES

The sides of the individual and interpenetrating parts of the stylolites are characteristically marked by alternating ridges and grooves which are *usually* parallel; on curved columns they parallel the curvature. These striations, accord-

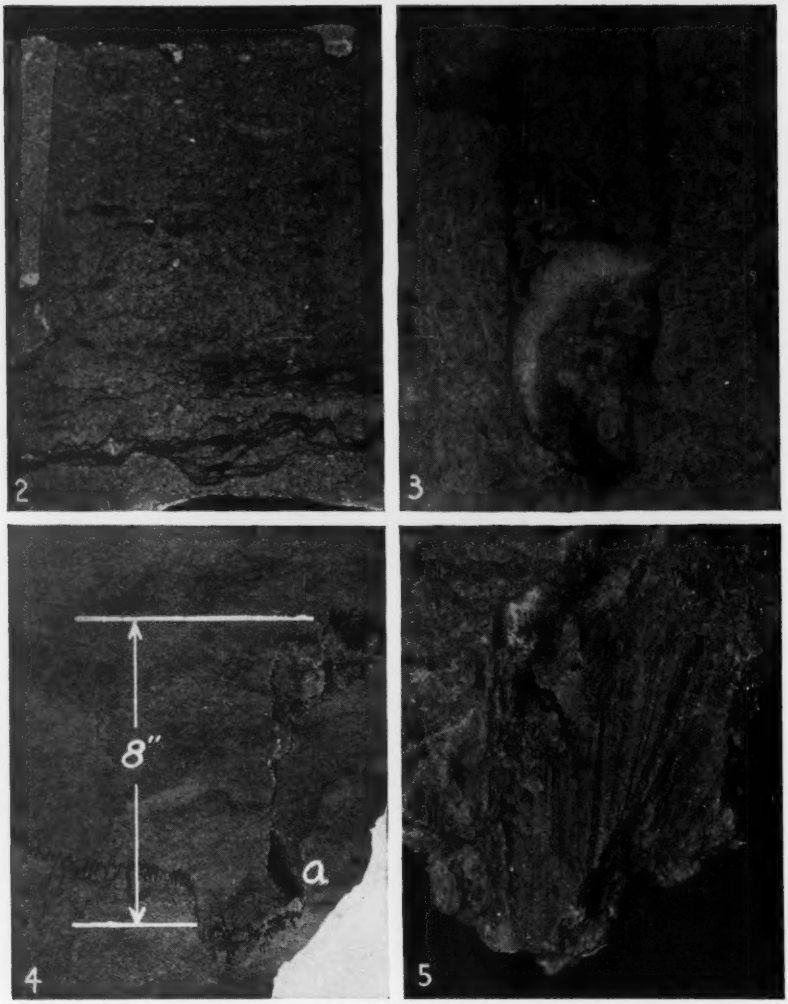

FIG. 2.—The clay terminating the short column is thicker than that terminating the longer one, showing that there is no relationship between the thickness of clay and the length of the columns. The lower part of the specimen resembles a flow structure and shows several poorly developed stylolite seams, along clay stringers, superimposed upon one another. Specimen from the Dark Hollow District, west of Oolitic, Indiana. (×1¼)

FIG. 3.—A small column in the Indiana öolitic limestone having a comparatively large shell standing on end in the point of the column. It is highly improbable that a shell of this size

(*Continued on opposite page*)

ing to the solution theory, are the result of solution at the bottom of the depressions, with downward movement of the overlying beds. According to this conception of the origin of the striae, the outside diameter of a column would have to exceed the diameter of the cavity by approximately twice the depth of the grooves. Columns one inch in diameter frequently have grooves up to and in excess of 1/25th inch deep, which means that the outside diameter of the column was about 8 per cent greater than the inside diameter of the solution cavity. In good engineering practice the maximum diameter of a shaft over a one inch hole for a *heavy force fit* is 0.0016 inch (21) or 0.16 per cent. This percentage is only 1/50th of the difference between the diameter of the stylolite column and its "solution" cavity, as given above; hence, it seems very unlikely indeed that stylolite columns could be forced into the solution cavities without severely fracturing either, or both, the columns and the adjoining rock, even if the difference in diameters were greatly reduced from the measured values. The very tight fit common to unweathered stylolite columns and seams would prohibit the *free circulation* of the solutions, for the difference in hydraulic pressure along any seam must be very low indeed. Striations like those associated with stylolite columns are readily reproduced in plastic materials like clay by the dragging action accompanying extrusion through dies during the process of forming bricks, drain tile, partition blocks, etc., while their production in solid materials is unknown to the writer. The striations associated with slickensides along fault planes are distinctly different in several respects.

The stylolite columns have been referred to frequently as being slickensided,* although they do not possess a real "slicken" surface. The clay partings may show a glistening appearance in some cases, but this is not a characteristic feature of the striae. The fact that similar striae can be readily produced in plastic materials suggests that a more appropriate name would be *drag striae.*

If the drag striae were the result of columns being forced into the receiving material when both were consolidated, according to the solution theory, the striae would have to be parallel on the straight columns and parallel to the curvature if the columns were curved. The specimen illustrated in Fig. 5 shows the striae to be converging at rather large angles instead of being parallel. It does not seem possible that striae having such a large divergence could be produced in such a *small volume* in hard rock as the result of movement produced by solution and the static force of the overlying material. The converging drag striae appear to be related to some markings on cone-in-cone structures.

* In my paper on the origin of cone-in-cone (22—Fig. 4) I referred to the shear surface on the conical structures as being "slickensided," a term formerly applied to these surfaces. It would have been better at that time to have referred to these as *plastic shear surfaces* to distinguish between them and the slicken surfaces developed along fractures in consolidated rocks under high pressure. The cone-in-cone structures described by Hendricks (23) would, no doubt, be slickensided along the original conical plastic shear surfaces as result of movement under high pressure during the subsequent intense folding.

---

would remain standing on the sharp edge as the result of sedimentation when it is associated with such relatively fine material. Note the öolites standing on end within the column. From near Oolitic, Indiana. (×9)

FIG. 4.—Stylolite seam connected by a slip in the plastic lime ooze. The sides along the slip possess the usual drag striae. Where the sides were pulled apart, as at *a*, each side still retains the drag striae originally impressed upon it by the dragging action. Terminated calcite crystals were deposited later over the drag striae. If the cavity at *a* had been formed by solution the drag striae would be absent. From the Stinesville District, Indiana.

FIG. 5.—An irregular stylolite column from the Lockport dolomite showing converging striations. From dump along south bank of canal at Lockport, N. Y. (×1½)

In Fig. 6 is illustrated an interesting and extremely important type of marking noted on some of the stylolite columns and walls in the Lockport dolomite found on the dumps along the south side of the Erie canal at Lockport, N. Y. Markings of this kind have not been previously described in connection with stylolites. A good descriptive term for these marks would be *adhesion ridges*, for they are presumably formed by the adhesion of the adjoining parts during the process of contraction when there was a tendency for the column and its walls to pull apart. These markings are excellent manifestations of volume contraction between the column and its wall after the penetrating motion had ceased; otherwise they would have been destroyed and only the drag striae would persist. Adhesion ridges are readily made by touching clay or other sticky, plastic materials with the hands or other objects and then breaking contact. An example of this kind, together with drag striae, made in Connecticut Valley varved clay, is shown in Fig. 8. The fact that adhesion ridges and drag striae can be readily reproduced in plastic materials, and that adhesion ridges are probably not reproducible in a solidified material, gives most substantial support to any theory that places the time of development of stylolites during the plastic stage of the lime ooze instead of after the material has hardened.

CURVED STYLOLITE COLUMNS

Field studies revealed a surprisingly large number of sharply curved stylolite columns. In a quarry of the Indiana Limestone Company, in the Dark Hollow District, west of Bedford, Indiana, a well-developed column was observed which had curved to such an extent that it pointed in the opposite direction from which it started.

About five miles south of Bloomington, Indiana, the lithographic phase of the limestone in the quarry of the Bloomington Limestone Company contains many curved stylolites which commonly occur as single columns. As this kind of limestone is exceedingly brittle, it was thought that a column curved as sharply as the specimen shown in Fig. 7 might contain some internal structure which would show whether the material was soft or consolidated when the curvature was developed. A column having the proportions of this stylolite and consisting of such a brittle material, if fractured at all by slow bending, would show centripetal fractures upon being bent to such a short radius. Centripetal fracturing would start from the convex side and would show in a longitudinal section as well defined radial cracks. Instead of finding radial tension fractures, very characteristic tension drag cracks appeared, making angles of about 45 degrees with the curvature of the column. They are well distributed along the convex side where the friction from the dragging action was the greatest. These cracks are typical of the drag cracks developed along the sides of extruded clay products and therefore strongly support an origin in unconsolidated lime ooze rather than in hardened rock. Another feature of this curved column is the occurrence of three small stylolite seams crossing it. The middle seam is of particular interest, as it cuts across both the large column and the wall alike and is therefore later in its development and undoubtedly occurred near the end of the contraction period when the main column remained more or less fixed. This general time relationship may apply to most of the small seams within the larger columns, making the former later in origin instead of being earlier as claimed by Stockdale (11–58).

SOME OTHER SIGNIFICANT OCCURRENCES OF STYLOLITE COLUMNS AND SEAMS

An interesting and important occurrence of a stylolite column is shown in Fig. 9. This column occurred along a seam which had many more or less isolated but well-developed columns. The one illustrated lacks the usual proportions by having a diameter greater than its

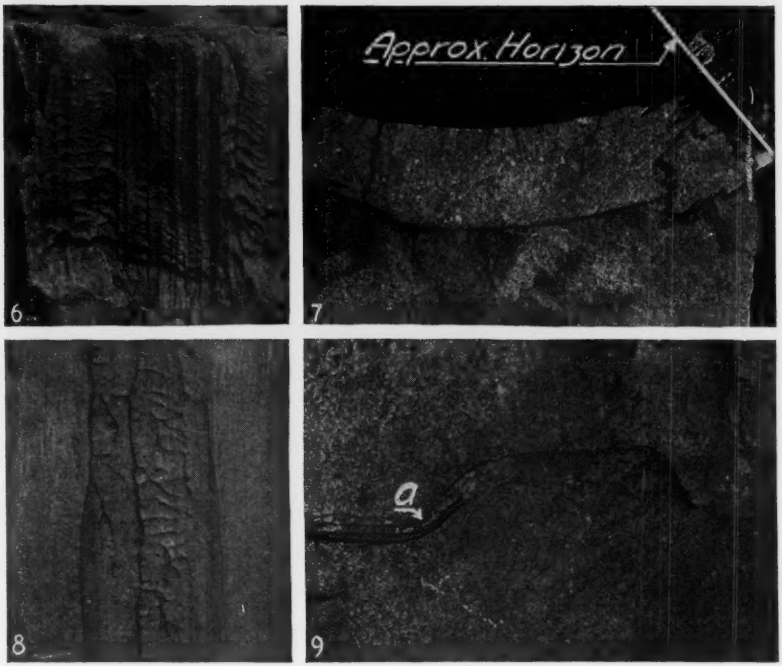

FIG. 6.—An illustration of part of the walls adjoining a stylolite column in the Lockport dolomite. The striations are crossed by transverse ridges believed to be caused by adhesion between the column and the wall during continued volume contraction after the column had pierced the adjoining unconsolidated plastic material. Specimen from the dumps along the south bank of the Erie canal at Lockport, N. Y. (×2)

FIG. 7.—A longitudinal section of a curved stylolite column from the lithographic limestone 5 miles south of Bloomington, Indiana. Along the convex side a series of drag cracks developed, while on the concave side the material was disturbed by plastic flow. Secondary or later stylolite seams are associated with the major one. (×1¼)

FIG. 8.—Adhesion ridges made in plastic Connecticut Valley varved clay with a block of wood by breaking contact with the clay. Note the similarity between the ridges thus produced and those shown in Figure 6. (×4½)

FIG. 9.—A stylolite column which shows how the laminations of the rock may bend to follow the outline of the column as it moves by plastic flow into a zone of reduced pressure. Note the thinning of the laminae at the sharp bend, at *a*. Specimen from the dumps along the south bank of the Erie Canal at Lockport, N. Y. (×2½)

length; nevertheless it is a true stylolite column and shows very clearly that the laminations of the rock have taken a reverse bend about the point of the stylolite column to conform with its vertical cross-sectional outline from top to bottom. There is a distinct thinning of the laminae at the sharp corner, marked *a*, about which they bend. These features show clearly that the material from the one bed moved into a zone of reduced pressure in the other by plastic flow of unconsolidated lime ooze.

CONCLUSIONS

Although the solution-pressure theory has been accepted by many geologists as the answer to the origin of stylolites,

the writer is unable to find the necessary evidence for its support. The theory's first and basic principle that limestones are differentially soluble with the more and less resistant parts located opposite each other along a bedding plane, lamination plane or crevice appears to be wholly unsupported, and in addition there is much contradictory evidence which has been pointed out.

The penetration of fossils by stylolites is believed to be only apparent. Shells which have been deposited on the floors of seas frequently contain holes and are often broken. To use the apparent penetration as critical evidence in support of the solution theory, one would have to prove that the particular fossils in question did not contain holes prior to the development of stylolite columns which penetrate them.

Striations, *such as occur along the sides of stylolites*, are believed by the writer to be unknown as a product of solution or as resulting from the dragging action between brittle materials. Strikingly similar striations, as well as drag cracks, develop on clay products which are made by extruding the material through dies. It does not seem feasible that the striations could have developed as the result of forcing a column into a solution cavity sufficiently undersized to develop striations having the depth of those found on stylolite columns and the adjoining walls. The occasional occurrence of strongly diverging striations likewise indicates an origin before the material hardened.

Good evidence has been presented to show that fossils, associated with stylolite columns, have been disturbed after deposition and before the rock had hardened; the disturbance was evidently associated with the development of the stylolites. Important evidence is given in Fig. 9 to show that laminations in the limestone have been bent to follow the outline of the stylolite column as the column was forced into the adjoining bed. The absence of bending of the beds has been used as negative evidence in support of the solution theory (24–787); consequently the presentation of an unmistakable occurrence of bending of the laminations is strong contradictory evidence against the same theory.

The writer wishes to make special reference to the new markings found on the stylolites from Lockport, N. Y., and illustrated in Fig. 6. They are common on a number of the columns from this locality. These marks have been termed adhesion ridges by the writer because similar marks as shown in Fig. 8 are readily made on the surfaces of sticky, plastic substances, whereas they cannot be made on solid materials. The adhesion ridges are believed to be *unique in character and origin* and to supply the *necessary critical evidence to establish the origin of stylolites prior to the consolidation of the enclosing rock.*

The tentative outline of the contraction-pressure theory for the origin of stylolite seams and columns, according to the known physical phenomena associated with the dewatering of highly plastic sediments, accounts for all the features, markings and occurrences of stylolites previously described and known to the writer; it likewise completely accounts for the unusual features of the stylolites illustrated above.

ACKNOWLEDGEMENTS

The writer wishes to express his sincere appreciation and thanks to Professors H. Ries and C. M. Nevin, of the Department of Geology, Cornell University, and to Professor H. A. Meyerhoff of Smith College for offering many helpful and constructive criticisms; and to Professor R. F. Collins of Smith College for assistance in the revision of the manuscript.

REFERENCES

1. Price, Paul H., *1934*, Stylolites in sandstone: *Jour. Geology*, vol. 42, 188–192.
2. Tarr, W. A., *1916*, Stylolites in quartzite: *Science*, 43, 819–920.

3. KLÖDEN, F., *1828*, Beitrag zur Mineral. u. Geol. Kenntniss: der Mark Brandenburg, Bd. 1, 28.
4. EATON, AMOS, *1824*, Report on the district adjoining the Erie Canal: *Geology of New York*, 134.
5. BONNEYCASTLE, R. H., *1831*, Continuation of the essay on the transition rocks of the Cataragui: *Am. Jour. Sci.*, 20, 74–82.
6. PLIENINGER, *1852*, Ueber Stylolithen: *Jahresh. d. Verein f. vaterl. Naturk. in Württemberg*, 78.
7. ZELGER, *1870*, Ueber Stylolithen: *N. Jb. F. Mineral.*, etc., 833.
8. v. ALBERTI, F., *1858*, Ueber die Entstehung der Stylolithen: *Jahresh. d. Verein f. vaterl. Naturk. in Württemberg*, 292.
9. QUENSTEDT, A., *1837*, Die Stylolithen sind anorganische Absonderungen: *Wiegmann's Arch.*, 137–142.
10. FUCHS, THEODOR, *1894*, Ueber die Natur und Entstehung der Stylolithen: *Sitzungsber d. k. Akad. d. Wiss. Math.-Nat. Kl.*, Wien, Bd. 103, 673–688.
11. STOCKDALE, PARIS B., *1922*, Stylolites: their nature and origin: *Indiana Univ. Studies*, 9, Study No. 55.
12. ———, *1926*, The stratigraphic significance of solution in rocks: *Jour. Geology*, 34, 399–414.
13. BRETZ, J. HARLEN, *1938*, Caves in the Galena formation: *Jour. Geology*, 46, 824–841.
14. GRABAU, A. W., *1920*, Geology of the non-metallic mineral deposits: McGraw-Hill Book Company, New York, 108.
15. TWENHOFEL, W. H., *1932*, Treatise on Sedimentation, 2nd ed.: Williams and Wilkins, Baltimore, 738.
16. NÁDAI, A., *1931*, Plasticity: McGraw-Hill Book Company, New York, 3–6.
17. RIES, H., *1927*, Clays, their occurrences, properties and uses. 3rd ed.: John Wiley & Sons, New York.
18. BLEININGER, A. V., *1925*, The properties of clays: Colloid Symposium Monograph, The Chemical Catalog Company, New York, 2, 90.
19. KINDLE, E. M., *1923*, Notes on mud crack and ripple mark in recent calcareous sediments: *Jour. Geology*, 31, 138–145.
20. NEVIN, C. M., *1936*, Principles of structural geology, 2nd ed.: John Wiley & Sons, New York, 222.
21. ALBERT, C. D., *1927*, Machine design drawing room problems, 2nd ed.: John Wiley & Sons, New York, 26f.
22. SHAUB, B. M., *1937*, The origin of cone-in-cone and its bearing on the origin of concretions and septaria: *Am. Jour. Sci.*, 34, 331–344.
23. HENDRICKS, T. A., *1937*, Some unusual specimens of cone-in-cone in manganiferous siderite: *Am. Jour. Sci.*, 33, 458–461.
24. GRABAU, A. W., *1913*, Principles of stratigraphy: A. G. Seiler and Company, New York, 787.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 9, NO. 2, PP. 62–76, FIGS. 1–7, TABLES 1–2, AUGUST, 1939

A MODIFIED LOGARITHMIC PROBABILITY GRAPH FOR THE INTERPRETATION OF MECHANICAL ANALYSES OF SEDIMENTS*

GEORGE H. OTTO
Soil Conservation Service, Cooperative Laboratory
California Institute of Technology
Pasadena, California

ABSTRACT

Mechanical analyses of sediments are studied by comparison with other analyses. Both graphical and numerical methods of comparison are in use, each kind having its limitations. Two terms of a Gram-Charlier series, expressed in Krumbein's phi units, represent the data in many types of analyses, thus enabling them to be reduced to three numerical values or parameters. Graphical methods are given for recognizing such analyses, for obtaining the parameters, and for evaluating the extent to which they summarize the analytical information. A general procedure is outlined for systematic interpretation of mechanical analyses. The advantages of this method of interpretation are shown by considering in detail the information that can be deduced from the graphical study of a sieve analysis of a dune sand.

INTRODUCTION

Mechanical analyses are studied and evaluated by comparing them either with analyses of type sediments or with those of a related group. Both graphical and numerical methods are employed. The former seek similarities in geometrical form between graphs of two or more analyses. When two or more analyses give the same graph, it is usually inferred that the environment affecting particle diameter composition is essentially the same. Although entire analyses are used in most graphical comparisons, the methods are by no means equally efficient; histograms, for example, not only may fail to disclose pertinent information, but may even suggest erroneous comparisons (10, p. 68).

Numerical methods of comparison (9, 11) attempt to reduce each mechanical analysis to a set of numerical values or parameters that summarize the information. These numerical values may be obtained by computation or by graphical methods. Sets of numerical values are compared with those of type sediments or with others of the same series. Close numerical agreement between two or more sets is generally taken as evidence of similarity in the environment affecting mechanical composition.

Such methods further presume that the parameters chosen to represent the mechanical analysis are capable of reproducing essentially all information in the analysis except sampling fluctuations. When the parameters are incapable of doing this, potential information is thereby lost. Consequently, it is not correct to infer that the environment affecting mechanical composition is essentially the same merely because a convenient set of parameters happens to have the same numerical values for a series of samples.

Numerical values which contain the essential information in a mechanical analysis may becalled the *relevant parameters*.[1] However, interpretation of me-

* Published with permission of the Soil Conservation Service, U. S. Dept. of Agriculture.

[1] This definition was suggested but not explicitly stated by R. A. Fisher (3, p. 6). Fisher distinguishes between *statistics* and *parameters*, the former being used to denote values computed from measurements on samples and the latter to denote the corresponding true values of the parent population from which the samples were drawn. In this paper *parameter* has its ordinary mathematical meaning.

chanical analyses is not complete when each analysis has been reduced to relevant parameters which have been compared with each other or with those of type sediments. Complete interpretation includes correlation of the parameters with the physical environment in which the sediment was formed.

MATHEMATICAL PROPERTIES OF MECHANICAL ANALYSES

Certain mathematical properties of mechanical analyses deserve mention:

1. Particle diameter is a property in which the ratio of change, rather than the amount of change, is fundamental (13, pp. 85–90; 9). Use of a logarithmic measure of diameter such as the phi unit (10, p. 76) and the parameters based on it (9, 11) avoids many rational difficulties in the interpretation of mechanical analyses.

2. Mechanical analyses are usually expressed in weight percentages instead of number percentages. This fact complicates application of sampling error theory, but does not prevent using statistical methods for condensing the data.

3. A particle has many kinds of diameters (4, 5; 17, 13, pp. 93–95; 6), while very different looking particles might correctly be said to have the same diameter.

4. Unless the samples are collected with proper consideration to the mechanism of deposition (14), the size distribution may be complex.

5. Small percentages at both ends of the analysis have physical significance; for instance, one per cent of clay in a fine sand will greatly alter cohesion and plasticity. Consequently, such statistics as the median and quartile deviation (9), which are virtually unaffected by changes at the ends of the distribution, cannot efficiently measure the dependence of these properties on the mechanical composition.

The parameters based on the first few logarithmic moments (11) of a mechanical analysis are computed from the entire analysis and always contain much of the information in it. In order to determine whether they are the relevant parameters, it is usually necessary to know the frequency function or mathematical law which expresses the distribution of particle diameters. Such functions have not yet been derived from consideration of the environment of deposition. However, two terms of a Gram-Charlier series[2] expressed in phi units, have proved suitable for a wide variety of sediments deposited in relatively simple environments. In such cases the three parameters of this function contain the essential information in the analysis and are thus the relevant parameters. For many other sediments the deviations of their analyses from this frequency function can be accounted for by considering subordinate environmental factors and differences in the mechanical composition of the several layers from which the field sample was taken.

THE PHI PROBABILITY GRAPH

The phi probability graph is a modification of the logarithmic probability graph invented by Hazen (7) in which cumulative percentage is plotted against the logarithm of the independent vari-

[2] In the form adopted in this paper the parameters and limits of integration are expressed entirely in phi units; thus, from the point of view of ordinary units of length, the series is a logarithmic one. It is of the usual type as far as computation and actual reasoning are involved. In the integral form the first two terms may be expressed as follows:

$$Y=\frac{100}{\sqrt{2\pi}}\int_0^z e^{-\frac{1}{2}z^2}dz-\frac{100k_\phi}{6\sqrt{2\pi}}\left[1-(1-z^2)e^{-\frac{1}{2}z^2}\right]$$

where Y = cumulative percentage (area) between the phi arithmetic mean diameter and diameter ϕ.

and $z=\frac{\phi-M_\phi}{\sigma_\phi}$, with

M_ϕ = phi arithmetic mean diameter.
σ_ϕ = phi standard deviation.
k_ϕ = phi skewness = Krumbein's α_3 or twice his Sk_ϕ (11, p. 40).
ϕ = any diameter defined by the expression $\phi=-\log_2\xi$, where ξ is the diameter in millimeters.

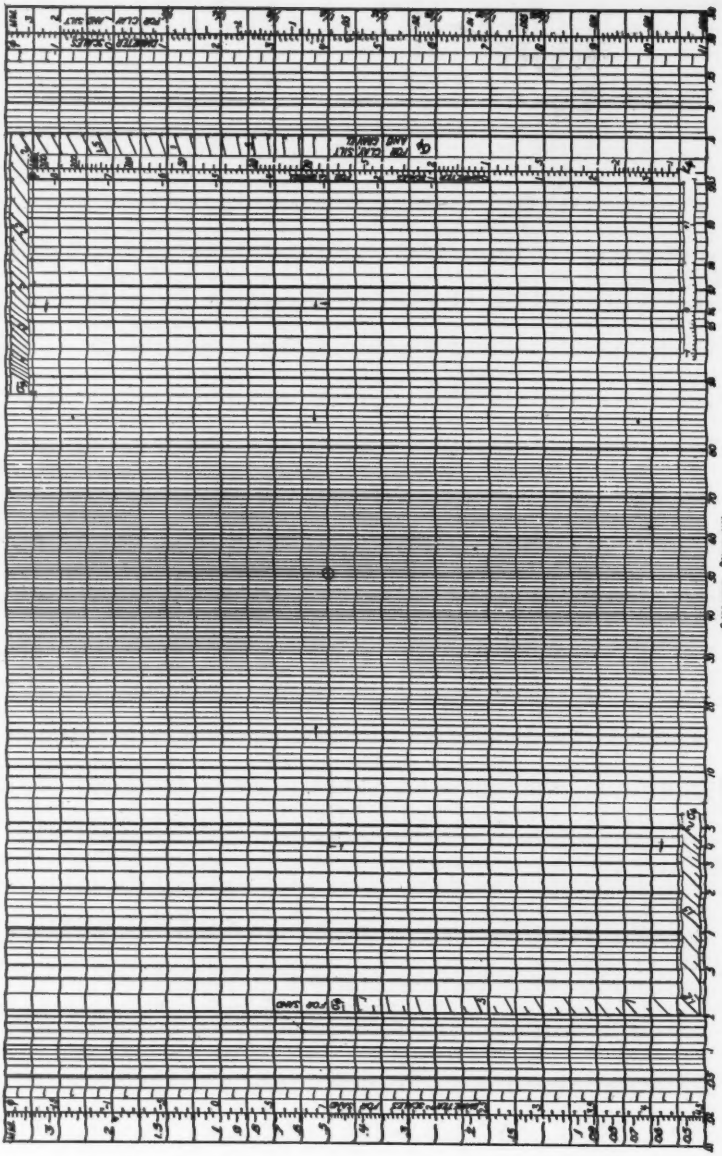

FIG. 1.—A sheet of phi probability graph paper.

able. Such graphs have been used for several kinds of mechanical analyses (8; 13, p. 189; 6; 4). On phi probability graph paper, the phi scale of diameter replaces the logarithmic scale; extra scales are added for obtaining certain parmaeters directly in phi terms. Such graphs without the parameter scales have been used by Krumbein (12) and Rouse (16, p. 349) for analyses which plot as straight lines. This paper extends the use of phi-probability graphs to other types of mechanical analyses. A method of constructing the graph paper, together with mathematical proofs, is given in the appendix.

Figure 1 shows a plain sheet of the graph paper. To accommodate the wide range in particle diameter of natural sediments, three sets of diameter scales have been placed on the same sheet, two of which possess a diameter interval twice as large as the third. Thus, the scales marked *DIAMETER SCALES FOR SAND* are used for sediments whose particles range from .044 mm to 4 mm. The scales labelled *DIAMETER SCALES FOR CLAY AND SILT* extend from 1/2048 mm to 4 mm; those labelled *DIAMETER SCALES FOR GRAVEL* extend from 1/16 mm to 512 mm.

Horizontal lines on the graph correspond to grade sizes in common use by geologists and engineers in the United States. The interval between lines corresponding to the left-hand scales is $\frac{1}{4}\,\phi$. The openings of the widely used Tyler sieves possess dimensions of very nearly $\frac{1}{4}\,n\phi$, where n is an integer, so that the horizontal lines closely approximate sieve sizes. For either right-hand set of scales, the interval between horizontal lines is $\frac{1}{2}\,\phi$. If the grade-size boundaries come at $\frac{1}{4}\,\phi$ intervals, intermediate lines are drawn as needed by connecting the pairs of short guide lines located alongside the .03 and 99.97 per cent vertical lines. Cumulative percentages are shown by the vertical lines of the graph spaced according to the probability scale at the bottom of the graph.

PLOTTING THE ANALYSIS

Plotting the analysis is expedited if the data are arranged as in table 1. This analysis is plotted on Fig. 2, where, for simplicity, only those scales are shown

TABLE 1. *Sieve analysis of dune sand from Palm Springs, California*

1	2	3	4
Diameter of sieve openings	Equivalent phi diameter	Percentage retained on sieve	Percentage finer
1.65 mm	− .75		100.00
1.17	− .25	.07	99.93
.833	.25	.43	99.5
.589	.75	5.4	94.1
.417	1.25	14.5	79.6
.295	1.75	23.5	56.1
.208	2.25	27.6	28.5
.147	2.75	15.6	12.9
.104	3.25	7.1	5.8
.074	3.75	2.7	3.1
pan		3.1	

which are used in the study of the analysis; many percentage lines are also omitted. The procedure is as follows:

Find in column 4 the percentage *3.1* corresponding to the smallest sieve diameter, *.074 mm*($\phi = 3.75$), in column 1 of table 1. Select the horizontal line on the graph corresponding to $\phi = 3.75$ and locate the circle one-fifth of the distance between the 3.0 and 3.5 per cent lines. Locate the next percentage, *5.8*, on the line $\phi = 3.25$. Since in this analysis the ratio interval between sieves is constant and equal to $\frac{1}{2}\,\phi$, place each succeeding percentage on the next unaccented line. (The 100 per cent point cannot be plotted, which is in accord with the fact that a larger sample generally has still larger particles.) Fit a smooth curve to the data, preferably first connecting the points with straight line segments. In fitting the curve, remember that points based on fewer than 20 particles in a grade are subject to large sampling errors and that for fine grades in amounts less than .5 per cent the laboratory technique is seldom good enough to benefit from

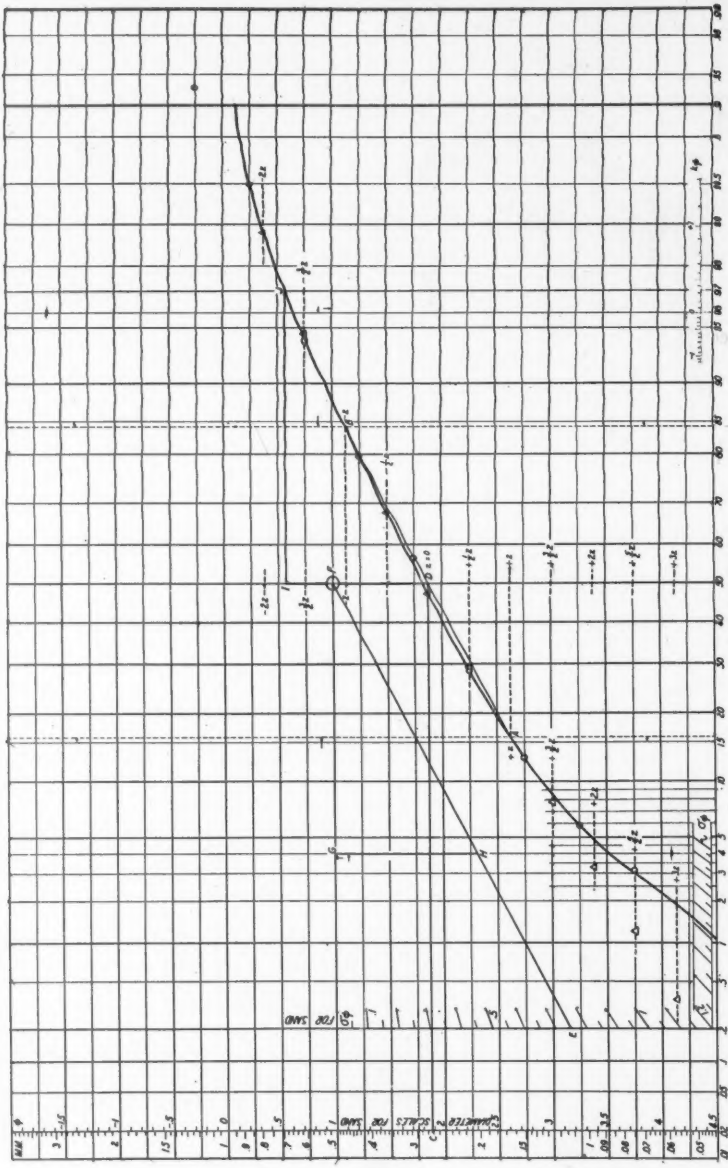

FIG. 2.—A sieve analysis of dune sand from Palm Springs, California, plotted on phi probability graph paper. The steps in the graphical determination of parameters and construction of the theoretical curve are shown.

the large number of particles actually present. In general, the fitted curve may depart from any point by an amount as large as the combined laboratory errors.

The phi probability graph greatly reduces curvature in graphs of most analyses, as shown by contrasting the conventional plot in Fig. 3 with that in Fig. 2. Extrapolation is less uncertain, both for this reason and because the small percentages at both ends of the analysis are represented with an accuracy equal to the best analytical technique.

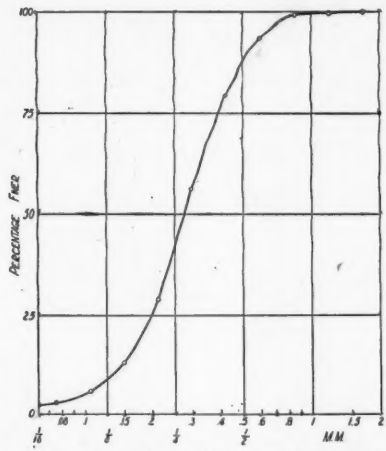

FIG. 3.—Semi-logarithmic graph of same analysis shown in Figure 2.

If the fitted curve resembles any curve in Fig. 4, it is probable that the two-term series given on page 63 summarizes the information in the analysis. The numerical values of the parameters may then be obtained graphically; but these values, especially the skewness, should not be accepted without fitting the theoretical curve as explained later. If the curves do not resemble any in Fig. 4, proceed to the section, *SYSTEMATIC INTERPRETATION OF ANALYSES.* (Curves A and B of Fig. 5 are common types not represented by two terms of a Gram-Charlier series.)

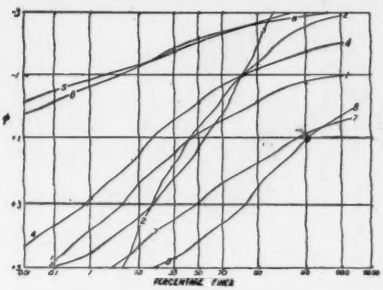

FIG. 4.—Graphs of a two-term Gram-Charlier series showing effect of changes in the parameters.

Curve	M_ϕ	σ_ϕ	k_ϕ	Curve	M_ϕ	σ_ϕ	k_ϕ
1	1	1	+1	5	−2	.5	0
2	1	2	+1	6	−2	.5	+1
3	1	2	−1	7	3	1	+ .3
4	0	1	+1	8	4	1	−1.2

GRAPHICAL DETERMINATION OF PARAMETERS

To obtain M_ϕ: Draw a straight line *AB* (fig. 2) connecting the intersections of the fitted curve and the 15.9 and 84.1 per cent dotted lines. These lines are identified by three small horizontal arrows. Where the 50 per cent line crosses the line *AB*, draw a horizontal line *CD* intersecting the diameter scale used in plotting the analysis. Read off the value of M_ϕ, *1.88*ϕ, on the arithmetic phi scale and the corresponding geometric mean diameter, *.272* mm, from the other side of the intersection.

To obtain σ_ϕ: Draw a line *EF* parallel to line *AB* through the center of the small circle near the middle of the graph. Extend the line *EF* to the phi standard deviation scale on the same side of the graph as the scale used for plotting the analysis. The phi standard deviation scales are labelled σ_ϕ and are the slant-line scales along the upper right and lower left corners of the graph. Read the value of σ_ϕ, *.75*ϕ, at *E* at the intersection of the line *EF* with the scale. The lower left scale labelled *FOR SAND* is graduated in intervals of .05ϕ and the other scale (see fig. 1) in intervals of .1ϕ.

To obtain k_ϕ: Set a pair of dividers to

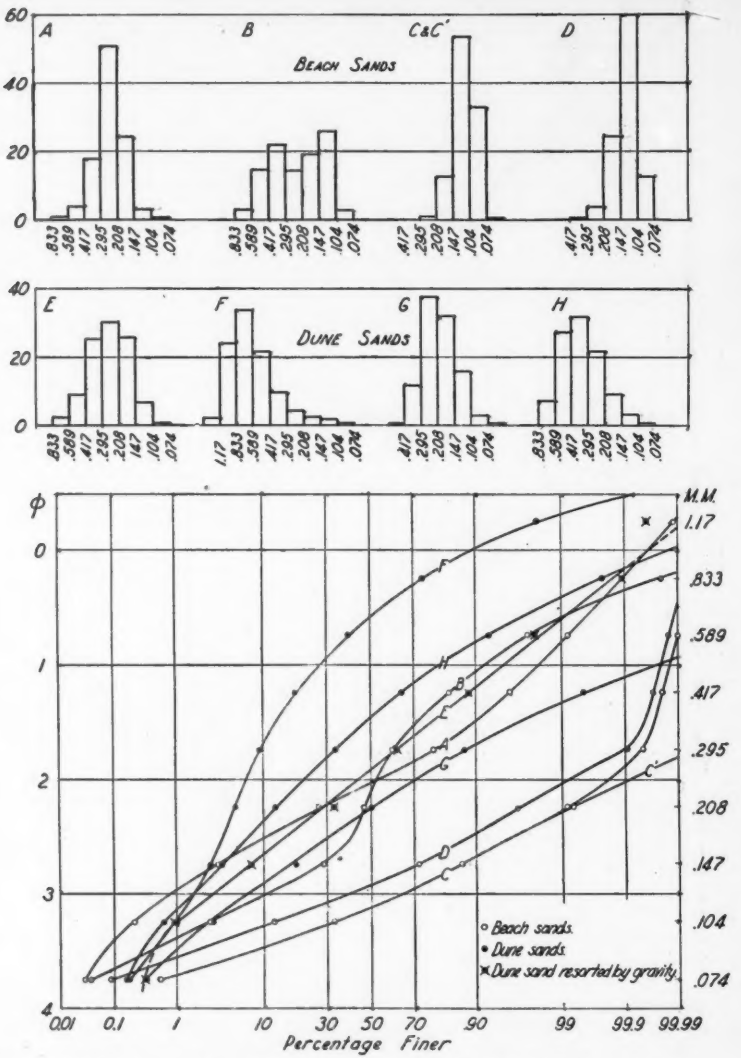

FIG. 5.—Graphical comparison of sieve analyses typical of beach and dune sands.

Location of Samples

A. West of Dune Point, Los Angeles County, California.
B. Daytona Beach, Florida. Sample collected following several days of offshore winds.
C. North end of Mustang Island, Texas, at Aransas Pass.
C'. Same sample after removing shells with dilute acid.
D. Eight miles South of Aransas Pass, Mustang Island, Texas.
E. Opposite highway bridge over Whitewater Wash, North of Palm Springs, California.
F. Ripple mark crests in the lee of a barchane in the dune complex West of Yuma, California.
G. Lee slope of above barchane.
H. Crest of active dune area near Oxnard, California.

the length *GH* on the vertical 4 per cent line between its intersection with the line *EF* and the horizontal line passing through the circle at the middle of the graph. The point *G* is indicated by two small arrows at right angles to each other. When σ_ϕ is read from the right hand scale (Fig. 1), use the 96 per cent line instead of the 4 per cent line; the point corresponding to *G* is indicated as before. Next, lay off the distance *DI*, equal to *GH*, on the 50 per cent line starting at its intersection with the line *AB*. From point *I* draw a horizontal line *IJ* intersecting the fitted curve. Read the percentage, *97.1*, at the intersection. On the k_ϕ scale near the lower right corner of the graph read the value of the skewness, *.36*, corresponding to the percentage just obtained.

The algebraic sign of the skewness depends on what is assumed to constitute a negative deviation from the phi arithmetic mean. The convention used by Krumbein (11, p. 40) is adopted here: those phi values algebraically larger than M_ϕ or the assumed mean are considered positive; similarly, that part of the distribution coarser than M_ϕ is considered negative. If a straight line fits the plotted points, the skewness is zero. In this case the fitted straight line takes the place of the line *AB*. The remaining procedure for obtaining M_ϕ and σ_ϕ is the same as described above.

GRAPHICAL CONSTRUCTION OF THE THEORETICAL ANALYSIS

In the previous section, it was assumed that two terms of a Gram-Charlier series form an adequate frequency function for representing the mechanical analysis. If this assumption is correct, the theoretical curve computed from these parameters should coincide with the curve drawn through the observed points. The amount of divergence thus furnishes a qualitative estimate of fit. Computation of the theoretical curve is tedious, however, and the results so obtained are not here suitable for applying the quantitative Chi Square test of goodness of fit (1, pp. 264–267), because mechanical analyses are expressed in weight percentages. A rapid graphical method was therefore developed for comparing the theoretical analysis with the observed data. Either calculated or graphically obtained values of the parameters may be used.

If calculated values are used, plot the analysis on phi probability graph paper and draw a horizontal line intersecting the curve at the position of the phi arithmetic mean diameter and label this line $z=0$. This line coincides with the line *CD* when the parameters have been obtained graphically. Moreover, the vertical distance between *A* and *B* in Fig. 2, when laid off along the proper phi scale starting at $\phi=0$, corresponds numerically to $2\sigma_\phi$. Consequently, to obtain a distance equal to $\sigma_\phi/2$, set a pair of dividers to a length on the phi scale corresponding to one-half the numerical value of σ_ϕ or to one-fourth the vertical distance between *A* and *B*. Now set one point of the dividers where the line, $z=0$, intersects the 50 per cent line; lay off successive intervals of the distance corresponding to $\sigma_\phi/2$ along the 50 per cent line. These distances correspond to intervals of $\frac{1}{2}z$ in the Gram-Charlier equation. Label the points as indicated in Fig. 2: $-\frac{1}{2}z$, $-z$, $-3/2z$, $-2z$, etc. above the line $z=0$ and $+\frac{1}{2}z$, $+z$, $+3/2z$, $+2z$, etc. below the line $z=0$. Draw horizontal lines intersecting the plotted curve and passing through these points.

Table 2 gives the corresponding cumulative percentages of the theoretical curve for skewness intervals[3] of $.1k_\phi$. Select the column corresponding most closely to the value of k_ϕ. Thus if $k_\phi=.36$, select the column marked $k_\phi=.4$. Starting with the lowest percentage given in that column, plot this percentage on the horizontal line (fig. 2) whose z value is the same as that given in the table. Plot the next higher percentage in the table

[3] An interval of .1 was adopted because repeated analyses of the same field sample often show larger deviations.

TABLE 2. *Cumulative percentages of the theoretical analyses based on two terms of a Gram-Charlier series*

z	k_ϕ												z
	+.1	+.2	+.3	+.4	+.5	+.6	+.7	+.8	+.9	+1.0	+1.1	+1.2	
−3.	99.924	99.983											−3.
−2.5	99.53	99.69	99.839										−2.5
−2.	98.00	98.26	98.54	98.80	99.08	99.34	99.62	99.885					−2.
−1.5	93.59	93.86	94.13	94.40	94.67	94.94	95.21	95.48	95.75	96.02	96.29	96.56	−1.5
−1.	84.1	84.1	84.1	84.1	84.1	84.1	84.1	84.1	84.1	84.1	84.1	84.1	−1.
−.5	68.7	68.3	67.8	67.4	66.9	66.5	66.1	65.6	65.2	64.7	64.3	63.9	−.5
0	49.3	48.7	48.0	47.3	46.7	46.0	45.3	44.7	44.0	43.4	42.7	42.0	0
+.5	30.4	30.0	29.5	29.1	28.7	28.2	27.8	27.3	26.9	26.5	26.0	25.6	+.5
+1.	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	+1.
+1.5	6.95	7.22	7.49	7.76	8.03	8.30	8.57	8.84	9.11	9.38	9.65	9.92	+1.5
+2.	2.54	2.82	3.08	3.36	3.62	3.90	4.16	4.44	4.70	4.98	5.24	5.52	+2.
+2.5	.77	.93	1.08	1.23	1.39	1.54	1.70	1.85	2.00	2.16	2.31	2.46	+2.5
+3.	.194	.25	.31	.37	.43	.49	.55	.61	.67	.73	.78	.84	+3.
+3.5	.039	.056	.072	.088	.105	.122	.138	.154	.171	.187	.20	.22	+3.5
+4.	.006	.010	.013	.016	.021	.024	.027	.030	.034	.037	.040	.044	+4.
	−.1	−.2	−.3	−.4	−.5	−.6	−.7	−.8	−.9	−1.0	−1.1	−1.2	
−4.	99.994	99.990	99.987	99.984	99.979	99.976	99.973	99.970	99.966	99.963	99.960	99.956	−4.
−3.5	99.961	99.944	99.928	99.912	99.895	99.878	99.862	99.846	99.829	99.813	99.80	99.78	−3.5
−3.	99.806	99.75	99.69	99.63	99.57	99.51	99.45	99.39	99.33	99.27	99.22	99.16	−3.
−2.5	99.23	99.07	98.92	98.77	98.61	98.46	98.30	98.15	98.00	97.84	97.69	97.54	−2.5
−2.	97.46	97.18	96.92	96.64	96.38	96.10	95.84	95.56	95.30	95.02	94.76	94.48	−2.
−1.5	93.05	92.78	92.51	92.24	91.97	91.70	91.43	91.16	90.89	90.62	90.35	90.08	−1.5
−1.	84.1	84.1	84.1	84.1	84.1	84.1	84.1	84.1	84.1	84.1	84.1	84.1	−1.
−.5	69.6	70.0	70.5	70.9	71.3	71.8	72.2	72.7	73.1	73.5	74.0	74.4	−.5
0	50.7	51.3	52.0	52.7	53.3	54.0	54.7	55.3	56.0	56.6	57.3	58.0	0
+.5	31.3	31.7	32.2	32.6	33.1	33.5	33.9	34.4	34.8	35.3	35.7	36.1	+.5
+1.	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	15.9	+1.
+1.5	6.41	6.14	5.87	5.60	5.33	5.06	4.79	4.52	4.25	3.98	3.71	3.44	+1.5
+2.	2.00	1.74	1.46	1.20	.92	.66	.38	.115					+2.
+2.5	.47	.31	.161										+2.5
+3.	.076	.017											+3.

on the next higher z line on the graph, continuing until all the values (shown by triangles in fig. 2) have been plotted.

Compare the theoretical curve corresponding to these points with that obtained from the analysis. The allowable amount of deviation depends on the magnitude of the laboratory errors and of the fluctuation in mathematical form of a series of closely spaced field samples. The fit obtained in Fig. 2 is generally typical of samples from single sedimentation units.

SYSTEMATIC INTERPRETATION OF ANALYSES

Until frequency functions representing size distribution can be derived mathematically for specific environments, the interpretation of mechanical analyses will necessarily be a comparative study. Consequently, the interpretation of a single analysis is best made by comparing it with analyses of other samples deposited under somewhat different, but definitely known, field conditions. Certain ideal types, which serve as norms of comparison, can generally be deduced. Any deviation therefrom which is greater than sampling and laboratory errors deserves explanation. The interpretation of related analyses, such as those of an environmental pattern study, should involve not only explanation of numerical changes in the parameters, but also changes in mathematical form of the frequency functions that represent the distributions of particle size.

Figure 5 shows nine analyses typical of beach and dune sands. Single samples of beach and dune sands cannot consistently be distinguished from each other by comparing their histograms or ordinary cumulative curves. Because the phi probability graph is sensitive to slight differences in mechanical composition of the end fractions, it is helpful in studying sediments of diverse origin but similar mechanical composition. Each sample used in Fig. 5 was collected from part of a sedimentation unit (14). Curves *F*, *G*, and *H* are typical of dune sands low in heavy minerals; such curves are concave downward and generally approach an upper limit of particle diameter when large samples are employed to determine the small percentages in the coarsest grades. Curve *E* is a micaceous dune sand resorted by a gravity slide on a steep mountain slope; the straight-line tendency is common in sediments sorted by gravity. Curves *A*, *B*, *C*, *C'* and *D* are typical beach sands. They tend to be concave upward unless there are complications in density and shape of particles, such as in curve *B*, for which the sand consists of rounded quartz grains and platy shell fragments. Curves *C* and *D* show notably different histograms, yet the only physical difference between the sediments is a moderate one in average diameter. On the graph this is shown by their similar shape and different position. Curves *C* and *C'* look alike on the histograms but are readily distinguished on the graph because they differ considerably in skewness. Complete criteria for distinguishing beach and dune sands cannot, of course, be developed from these few analyses alone, for they fail to illustrate many complicating factors, but these curves do give a simplified summary of an extensive study following the plan outlined in the remainder of the paper.

This plan for systematic interpretation was tested on four different environmental patterns, the time required being well repaid by the gain in geological information that otherwise might have remained undiscovered. No assumptions have been made concerning field sampling technique. However, if samples are collected without regard to sedimentation units (14), disappointingly few analyses may be amenable to the mathematical treatment described above. Thus, extremely variable types of analyses are obtained when the samples consist of only a few laminae or a small number of sedimentation units differing greatly in average diameter; on the other hand, when a large number of sedimentation units is included in each

sample, the mechanical analyses may again show striking uniformity with respect to mathematical type.

The steps recommended for systematic interpretation are as follows:

1. *Classify the mechanical analyses according to mode of deposition.* For example, in a study of windblown deposits along a desert wash where it leaves the mountains and debouches on the desert floor, sediments such as the following should be distinguished: waterborne sand and gravel in the wash (the source of the windblown deposits), lag sand and gravel, dune sand, dune sand resorted by gravity on steep mountain slopes, rock talus mixed with dune sand, and sandy loess deposited around clumps of vegetation.

2. *Plot analyses of typical samples of each kind of sediment on phi probability graph paper, using a single sheet for each sediment type.* Wherever possible, plot one or two analyses of sediment deposited under essentially constant conditions and consisting entirely of minerals of the same density and shape characteristics.[4] These samples may be from any locality, provided the environment of deposition is definitely known to be similar and provided comparable kinds of particle diameter are employed in both sets of analyses.

3. *Note whether most of the curves on any one sheet can be classified into one or two distinct geometrical types.* Thus, compare the analyses included in each type with analyses of those samples which represent the simplest environment of deposition, and ascertain whether the differences can be assigned qualitatively to specific complicating factors in the environment. In this way, factors affecting mechanical composition are discovered that otherwise might remain unnoticed even with detailed field work.

4. *If the curves resemble those in Fig. 4, fit two terms of a Gram-Charlier series to representative analyses by the methods described above.* If the fit is poor or if the curves are obviously different from those in Fig. 4, consider whether the environment of deposition is such that the resulting sediment is actually a mixture of two separate distributions deposited simultaneously or alternately. Sand deposited from a muddy stream is such a sediment, since silt and clay settle out between the sand particles immediately following deposition of the sand; such analyses show a long "tail" of fine sizes. Experiments in progress indicate that the phi probability graph provides a rational quantitative approach to many two-component sediments.

5. *Plot the remaining analyses on phi probability graph paper and classify the curves according to the types previously deduced.* These graphs are conveniently drawn on $8\frac{1}{2} \times 11$ sheets of arithmetic probability paper, such as Codex #3127, if a phi scale is laid out along the equispaced rulings; for classification purposes only straight line segments need be fitted to the points. Now indicate the types on a map showing sample locations, also noting any transitional types and highly irregular analyses.

6. *Obtain sets of relevant parameters whenever practicable.* If only a few analyses are reducible to sets of relevant parameters, compute only those parameters based on the first three moments. Graphically determined parameters are preferable for studies of major factors affecting mechanical composition, because secondary effects are considerably reduced by the curve fitting process and the non-use of the extreme ends of the curve in the graphical constructions. In studies involving correlation of physical properties with mechanical composition, computed parameters are preferable, since they more truly reflect the influence of secondary characteristics of the mechanical analysis. Thus, a "tail" consisting of two per cent silt and clay in a mechanical analysis of fine sand may be unimportant in a study seeking to determine the principal factors controlling average diameter and sorting; yet the

[4] Shape is often correlated with particle diameter in sand and gravel deposits; such variations are permissible. The combination of platy and well-rounded grains in the same sample is to be avoided.

same amount would considerably affect such a property as porosity.

7. *Prepare areal contour maps of the parameters, noting those computed from analyses not satisfactorily represented by the frequency function.* In drawing the contours, an erratic value may be ignored if it is reasonably certain that the deviation was caused by defective field sampling. If the parameters consistently fail to form relevant sets, it should be kept in mind that conclusions drawn from the contour maps alone may be erroneous.

8. *From the contour maps, and from the map showing locations and types of curves, select one or more sets of analyses which show the change in mechanical composition from the source of the sediment to the highly sorted end products.* The analyses in each set should form a logical geographical group. Visual study of these graphs often reveals what is happening to the parameters, and as well to the frequency function itself, during the transportation process.

9. *Determine how much variation in appearance of the curves and what range in parameter values can reasonably be attributed to combined effects of field-sampling fluctuations and laboratory errors.* Field-sampling fluctuations include cyclical changes too local to be included in a regional investigation and also those fluctuations which remain unpredictable even after numerous closely spaced analyses have been studied. Laboratory errors include those deviations which can be evaluated by successive analyses of the same sample.

A usable estimate of the combined effect of these errors may be obtained from analyses of eight or more samples selected from an area one-fourth as large as that represented by the samples used in the regional study. If the environment changes rapidly in one direction and slowly in another, as along a coastal strip, take the sample from an elongated area or line parallel to the direction of minimum regional change. A set of such samples is required from each distinctly different environment of deposition. Plot the analyses on a single sheet and draw dotted lines tangent to the outermost deviations as in Fig. 6. Usually the curves cross each other without apparent system; failure to do so may indicate rapid regional changes or the presence of some cyclical variations of considerable magnitude. In a regional study two analyses are probably significantly different if their graphs show differences in position greater than the divergence between the dotted lines.

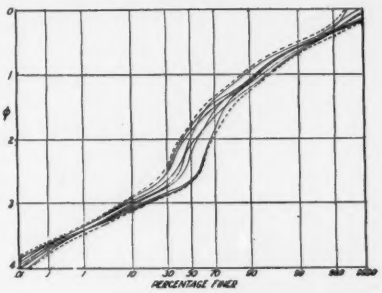

FIG. 6.—Sieve analysis of eight closely spaced samples of beach sand from Daytona Beach, Florida. The area between dotted lines indicates the amount of variability assignable to local sampling errors and laboratory errors combined.

10. *If a frequency function is found that satisfactorily represents mechanical composition where complicating environmental factors are fewest, examine all poorly represented analyses for specific environmental factors capable of causing the deviations.* Thus, in Fig. 2, the theoretical curve agrees well with the plotted curve except for the finest 5 per cent and the coarsest .5 per cent. From other dune-sand analyses, it appears that two terms of a Gram-Charlier series give a close approximation to the frequency function if the sand consists entirely of quartz and feldspars and if the samples are from one sedimentation unit.

The sample used in Fig. 2 was collected from the full thickness of one sedimentation unit. The coarsest grade contained only thin, weathered biotite flakes; other grades contained quartz and feldspars with subordinate mica. During trans-

portation, thin mica flakes behave like quartz particles of smaller sieve diameter. Consequently, the sieve analysis shows coarser diameters than the theoretical analysis indicates. The sand was dusty when collected, for it was derived from nearby Whitewater Wash and was deposited in the lee of a rock hill. During moments when wind velocities are too weak to transport sand, silt settles between the interstices of the sand grains

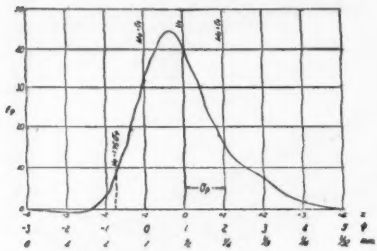

FIG. 7.—Graph of

$$f(\phi)=\frac{100}{\sigma_\phi\sqrt{2\pi}}e^{-\frac{1}{2}[(\phi-M_\phi)/\sigma_\phi]^2}\left[1-\frac{k_\phi}{2}\left\{\frac{\phi-M_\phi}{\sigma_\phi}-\frac{1}{3}\left(\frac{\phi-M_\phi}{\sigma_\phi}\right)^3\right\}\right]$$

when $M_\phi=1$, $\sigma_\phi=1$, $k_\phi=+1$.
This curve is the derivative of curve 1 in Fig. 4.

and is buried by sand transported over the hill during succeeding gusts of wind. Consequently, the sand is a mixture of two sediments, dune sand and loess, with the former greatly predominating, so that very fine sand and silt are present in greater amounts in the sample than in the dune sand alone. Another factor of similar tendency is the coating of fine silt weakly cemented to most sand grains. Such cementation occurred as the wash dried up, thus increasing the grain size, the relative effect being much greater on the finer grains. During sieving, many of these particles were knocked off and collected in the pan, thereby making the pan percentage greater than expected.

The purpose of step 10 is to systematize knowledge of secondary characteristics of the analysis and to help locate environmental factors which otherwise might be ignored as "unimportant." Emphasis here is on a specific mathematical type of curve deduced from a comparison of many analyses, whereas in step three no assumptions are made concerning the frequency function which represents the analyses, the object being to ascertain the geometric form of the basic type of curve and to test the type selected by inquiring whether deviations from it can be explained in terms of environment alone.

ACKNOWLEDGEMENTS

The writer wishes to acknowledge the assistance and suggestions of members of the staff of the Cooperative Laboratory, particularly computing by M. H. Duer and G. Osborne and drafting by R. W. Lindberg. A grant from the Works Progress Administration made possible a more thorough investigation than could otherwise have been made. Professors I. Campbell, F. J. Converse, W. Houston and H. J. Fraser of the California Institute of Technology and Dr. A. E. Brandt of the Soil Conservation Service read and criticised the manuscript.

APPENDIX

Principles on which the graph paper is based. In the following expression $F(\phi)$ gives the percentage of particles whose diameters lie between diameters M_ϕ and ϕ:

$$F(\phi)=\int_{M_\phi}^{\phi}\frac{100}{\sigma_\phi\sqrt{2\pi}}e^{-\frac{1}{2}[(\phi-M_\phi)/\sigma_\phi]^2}\left[1-\frac{k_\phi}{2}\left\{\frac{\phi-M_\phi}{\sigma_\phi}-\frac{1}{3}\left(\frac{\phi-M_\phi}{\sigma_\phi}\right)^3\right\}\right]d\phi. \quad (1)$$

The notation and convention concerning the sign of k_ϕ are given on pages 5 and 9. Figure 7 shows the graph of the frequency function, $\frac{dF(\phi)}{d\phi}$, for $M_\phi=1$, $\sigma_\phi=1$, and $k_\phi=+1$. By substituting a new variable for ϕ,

$$z=\frac{\phi-M_\phi}{\sigma_\phi} \quad \text{then} \quad d_\phi=\sigma_\phi dz \quad (2)$$

the above integral takes the following form,

for which tables are available:

$$F(\phi)=\frac{100}{\sqrt{2\pi}}\int_0^z e^{-\frac{1}{2}z^2}dz - \frac{100k_\phi}{6\sqrt{2\pi}}[1-(1-z^2)e^{-\frac{1}{2}z^2}]. \quad (3)$$

The first term is the integral of the normal curve of error; when $k_\phi=0$, the second term vanishes.

By means of a table for the first term and elementary calculus for the second, it is readily shown that the percentage of particles finer than M_ϕ is $50-6.649\ k_\phi$ and that the percentage of particles finer than M_ϕ but coarser than $M_\phi+\sigma_\phi$ is $34.134-6.649\ k_\phi$. The percentage finer than $M_\phi+\sigma_\phi$ (fig. 7) is then:

$(50-6.649\ k_\phi)-(34.134-6.649\ k_\phi)=15.866.$

Therefore, the cumulative percentage at one phi standard deviation finer than the phi arithmetic mean diameter will always be 15.866 per cent, regardless of the value of the skewness, if two terms of a Gram-Charlier series represent the analysis. Similarly the *percentage finer than diameter* $M_\phi-\sigma_\phi$ is always 84.134 per cent.

These two cumulative *percentages, 15.866* and 84.134, are loci of intersection of the family of curves formed from (3) by *varying* k_ϕ while M_ϕ and σ_ϕ are held constant. Application of the principles of analytical geometry to equation (2) shows that varying the value of M_ϕ affects merely the relative position of the curve on the graph (fig. 4, curves 1 and 4). Variations in σ_ϕ affect the scale of the graph (fig. 4, curves 1 and 2). Only variations in k_ϕ cause changes in the shape of the curve. These statements are independent of the kind of graph used, provided particle diameter is expressed in phi units.

Construction of the lines of the graph and the diameter scales. The vertical phi scales and horizontal lines of the graph are ordinary equal interval scales. The corresponding logarithmic millimeter scales are constructed as described by Croxton and Cowden (2, pp. 105–107). The vertical, cumulative percentage lines are so located that the integral in the first term of (3) will plot a straight line. This is accomplished by spacing the percentage lines proportional to their corresponding z values (7). In other words, each percentage line (denoting area under the normal curve) is spaced proportional to the numerical value of its abscissa.

In a graph extending from .01 to 99.99 per cent, the median or 50 per cent line lies midway between; furthermore, the lines on the left half of the graph are mirror images of those on the right half. Pearson (15, pp. 2–10) gives a table showing the values of the abscissae of the normal curve as a function of the frequency or cumulative percentage expressed as a decimal. In this table the abscissa is denoted by x and the cumulative percentage by $\frac{1}{2}(1+\alpha_x)$.

The z value corresponding to 99.99 per cent is 3.719. For a graph 28.5 inches wide, one z unit is represented by a length of $14.25/3.719=3.832$ inches. Since the z value for the 80 per cent line is .842, it is located $.842\times3.832$ inches to the right of the 50 per cent line. The 20 per cent line is the same distance to the left. Similar computations are made for each pair of lines.

Theory and construction of the phi standard deviation scale. When equation (1) represents the analysis, it has been shown that there are two loci, located at 15.9 and 84.1 cumulative per cent, which are always one standard deviation on either side of M_ϕ, regardless of the value of k_ϕ. On the graph the vertical distance between these points, measured by the distance between their intercepts on the phi scale, is thus equal to two standard deviations. Consequently, if a σ_ϕ scale were laid out along the 15.9 per cent line starting at the horizontal line $\phi=0$, the values of σ_ϕ and the spacings would be identical with those of the regular ϕ scale. Since the phi standard deviation is proportional to the tangent of the slope of the line connecting the two loci, the scale can be transferred to any convenient line by means of similar triangles.

In constructing the scale, points are located on the 15.9 and 84.1 per cent lines at a distance equal to two phi units below and above the horizontal line passing through the small circle. A line is drawn through these points intersecting the vertical line selected for the standard deviation scale. The distance from the horizontal line to this intersection is then divided into the correct number of divisions and the scale is drawn radially, using the small circle as a center.

Because this construction fixes the origin,

it is necessary always to translate the origin from the observed mean diameter to the circle by drawing the line EF parallel to AB (fig. 2).

Theory of the determination of M_ϕ. When k_ϕ is zero, the phi median and the phi arithmetic mean diameter coincide, so that both are obtained from the intersection of the straight line graph with the 50 per cent line. Since the family of curves formed by varying the skewness while M_ϕ and σ_ϕ are held constant have two points of common intersection, the straight line graph when k_ϕ is zero includes these points. Consequently, to obtain M_ϕ when k_ϕ is not zero, simply draw a straight line through the loci at 15.9 and 84.1 cumulative per cent and determine M_ϕ as above.

Theory and construction of the skewness scale. When equation (1) represents the analysis, the curvature of the graph is caused by the skewness alone. Consequently, the skewness can be measured by determining the cumulative percentage at which the graph crosses some multiple of the standard deviation, z, provided z is not equal to 1. Values of z are measured along the vertical scale of the graph starting at M_ϕ and expressed as multiples of the standard deviation in accordance with equation (2). For reliable determination of the skewness, the extreme ends of the distribution are unsatisfactory on account of sampling errors. Values near $z=\pm 1$ are too insensitive. A z value of 1.75 gives a good compromise and conveniently corresponds almost exactly to 4 and 96 cumulative per cent for the normal curve. Since the spacings of the vertical percentage lines are proportional to their corresponding normal curve z values, it follows from the geometry of the right triangle that the distance GH on figure 2 is 1.75 times the scale value of one standard deviation. The lines DI and IJ merely enable this value of 1.75 z to be measured from M_ϕ. The percentage finer than $M_\phi - 1.75\sigma_\phi$ is equal to the percentage finer than M_ϕ plus the percentage between M_ϕ and $M_\phi - 1.75\sigma_\phi$; from equation (3) these values are:

$$(50 - 6.649\ k_\phi) + (45.994 + 9.615\ k_\phi)$$
$$= 95.994 + 2.966\ k_\phi.$$

By substituting values of the skewness, the corresponding percentages are found which are then marked off to form the skewness scale.

REFERENCES

1. Camp, B. H., *1934, The mathematical part of elementary statistics*, D. C. Heath Co.
2. Croxton, F. E., and Cowden, D. J., *1934, Practical business statistics*, Prentice-Hall, Inc.
3. Fisher, R. A., *1932, Statistical methods for research workers*, Oliver and Boyd.
4. Goldman, F. H., and Dalla Valle, J. M., *1939*, An accurate method for the determination of the components of a heterogeneous particulate mineral system: *Am. Mineralogist*, vol. 24, 40–47.
5. Hatch, T., and Choate, S. P., *1929*, Statistical description of the size properties of non-uniform particulate substances: *Franklin Inst. Jour.*, vol. 207, 369–387.
6. Hatch, T., *1933*, Determination of average size from the screen analysis of non-uniform particulate substances: *Franklin Inst. Jour.*, vol. 215, 27–37.
7. Hazen, A., *1914*, Storage to be provided in impounding reservoirs: *Am. Soc. Civil Engrs., Trans.*, vol. 77, 1539–1669, especially 1664–1668.
8. Loveland, R. P., and Trivelli, A. P., *1927*, Mathematical methods of frequency analysis of size of particles, Part I, methods: *Franklin Inst., Jour.*, vol. 204, 193–217.
9. Krumbein, W. C., *1936*, The use of quartile measures in describing and comparing sediments: *Am. Jour. Sci.*, vol. 32, 98–111.
10. ———, *1934*, Size frequency distribution of sediments: *J. Sed. Pet.*, vol. 4, 65–77.
11. ———, *1936*, Application of logarithmic moments to size frequency distribution of sediments: *J. Sed. Pet.*, vol. 6, 35–47.
12. ———, *1938*, Size frequency distributions of sediments and the normal phi curve: *J. Sed. Pet.*, vol. 8, 84–90.
13. Krumbein, W. C., and Pettijohn, F. J., *1938, Manual of sedimentary petrography*, D. Appleton-Century Co.
14. Otto, H., *1938*, The sedimentation unit and its use in field sampling: *Jour. Geology.*, vol. 46, 569–582.
15. Pearson, K., *1932, Tables for statisticians and biometricians*, Part II, Cambridge University Press.
16. Rouse, H., *1938, Fluid mechanics for hydraulic engineers*, McGraw-Hill Book Company.
17. Wadell, H., *1934*, Some new sedimentation formulas: *Physics*, vol. 5, 281–291.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 9, NO. 2, PP. 77–85, FIGS. 1–3, TABLES 1–3, AUGUST, 1939

SEDIMENTARY ROCKS OF THE NIAGARA GORGE

JOHN T. SANFORD
Magnolia Petroleum Company
Oklahoma City, Oklahoma

ABSTRACT

Conditions of sedimentation responsible for the Niagara Gorge rocks are discussed in the light of data from mechanical analyses. These results are compared with thin section studies made by Alling. The method of preparation of the specimens for analysis is described.

INTRODUCTION

The Niagara Gorge, near Niagara Falls, New York, exposes a well known section. The present study of these sediments is based on mechanical analyses although a few chemical analyses are included.

A method for disintegration has presented difficulties. It has not been possible to find one that is completely satisfactory but a procedure which gives reproducible results has been used. This phase of the analytical work is discussed.

The formations have been interpreted in the light of the results of the mechanical analyses but this interpretation has been influenced considerably by stratigraphic studies in this region. The results agree fairly well with studies by Alling (1) on the petrology of these rocks.

METHODS FOR DISINTEGRATION

Some of the methods for disintegration and dispersion which have been devised for use with incoherent sediments can be applied to the disintegration of lithified rocks. Other methods have been contrived to facilitate the removal of fossils, but have too little regard for maintaining the original character of the sediments. Heating and quenching, saturation with water and freezing, and saturation with a solution of some salt followed by baking to promote crystal growth and thus force the rock apart have all been used, but methods of this type are too harsh for the present purpose. Any purely mechanical method will change the shapes and sizes of some of the grains.

Steam and pressure chambers have been used successfully for some purposes. Postel (2) placed the sample in a flask fitted with a two-hole rubber stopper to admit an inlet pipe and an exhaust tube. The inlet pipe took the form of a jet at the bottom of the flask so placed that any liquid present assumed a swirling motion. Steam under a pressure of about twelve pounds was admitted for 10 minutes and sodium carbonate could be added. Water was introduced by the condensing steam. The purpose of this method was to remove clay balls from sand. The clay was not saved. Taylor and Georgesen (3) made use of a pressure chamber. The apparatus consisted of a metal chamber in which beakers containing the sample and a liquid could be placed. Pressure was developed by heat applied to the bottom of the chamber which contained the liquid. Pressures as high as 350 pounds per square inch were developed and chemicals were added when necessary. Four conditions or causes of separation were noted; (1) high temperatures alone when the constituents had different coefficients of expansion, (2) enlarging of interstitial spaces when vapors or liquids were forced into them, (3) actions of solvents forced in to dissolve cementing material, (4) crystallization of sodium sulphate after it had been forced in insupersaturated solution. The writer has not had an opportunity

to investigate this method but if the second and third types of activity could be emphasized it might have much to recommend it, particularly when the time element is considered and the possible effects of the long soaking necessary in the procedure to be described.

The procedure adopted consists of removing some of the constituents chemically and thus allowing the others to fall apart, or a combination of this and some gentle mechanical method. This means that a sample is not retained in its entirety but in many cases this may increase the value of the analysis. A mechanical analysis should deal with that portion of the rock which was derived mechanically, and not with those constituents which were chemically or organically deposited. The clastic constituents of many sediments consist of materials which are relatively more resistant to erosion and also to solution, but the chemically and organically formed minerals are frequently more easily dissolved. The more soluble portions of a rock may consist of cementing materials or other secondary minerals added subsequently to the deposition of the sediment and their removal likewise furthers the object of the analysis. The only cases in which loss of material is detrimental are those in which clastic constituents are removed and even in such cases comparable results can be obtained. The more readily soluble minerals are apt to undergo changes in grain size, if not complete reorganization, during the diageneses and subsequent history of the rock, and hence a mechanical analysis of them, if possible, would not indicate the true composition of the original sediment. Chemical studies of the materials removed by solution in the disintegration process have been attempted in a few cases in an effort to obtain a more complete description of the rock as a whole.

TECHNIQUE

The procedure consists of crushing the specimen into fragments, never larger than 15 mm. in their largest dimension, and after drying the sample to a constant weight digesting it in 10 per cent hydrochloric acid. The size of the sample used depends upon the character of the material. This can be determined from a preliminary insoluble residue.

After digestion is completed the residue is washed by removing the liquid with a siphon, adding distilled water and repeating several times, allowing intervals of from 24 to 48 hours between operations for the liquid to become clear. If the liquid fails to clear, a few drops of hydrochloric acid can be added to insure flocculation.

An analysis of the silts and clays is then made by the pipette method (4) and of the coarser fractions by screening.

It is convenient in deflocculation to use a tube which can be stoppered at both ends by no. 8 rubber stoppers and to convert this into a sedimentation chamber, for separating the silts and clays from the sands, by removing the stoppers and replacing one of them with a no. 7 rubber stopper inserted large end first. This eliminates crevices in the bottom of the tube and makes a transfer of the material unnecessary.

The sands and any undigested fragments present are washed from the sedimentation tube into a tared crucible or weighing bottle. This is easily done after the rubber stopper has been removed. They are then dried, weighed, sieved and the fractions weighed. If undigested material is present, each fraction is examined, microscopically if necessary, and all fractions composed entirely of undigested rock are lumped together and weighed. Frequently there is a fairly sharp division between those fractions which are made up of aggregates and those which are composed of free sand. In some cases there are one or two intermediate fractions which contain both and in these cases it is usually possible to estimate the relative amounts of each. If the undigested portion, or any of the sand fractions, contain recognizable secondary minerals the amounts may be estimated, or they may be

separated and weighed at the discretion of the worker.

Sandstones with siliceous cements which do not yield to the hydrochloric acid treatment are washed and weighed to determine the percentage of loss. About two grams of this material are then treated with a 50 per cent solution of hydrofluoric acid for several hours and gently manipulated with a rubber pestle. The sample is then washed by decantation under a hood and treated in the same manner as the coarse fractions of the more easily disintegrated samples. The cementing materials which have already been in and out of solution are affected by the acid more readily than are the sand grains and frequently this treatment produces sufficient disaggregation to permit a determination of the sizes and characters of the grains.

Experiments with crushed quartz indicate that the effect on the sand grains is not great. Less than 4.5 per cent by weight of samples treated with the hyrofluoric acid solution passed a 0.250 mm. screen on which they had been retained previously to the acid treatment and some of this would probably have been passed during the first screening had it been prolonged sufficiently. This was shown by a repeated screening of some of the original material.

Fine clastic constituents which some sandstones contain may be lost by this procedure but the presence of appreciable amounts of these materials can be determined microscopically.

The results both from the screening and the pipette analysis are calculated as percentages in the ordinary way except in those cases where there is an undigested fraction left. In these cases the percentages of insoluble matter can be calculated from the weights of the undissolved material and the original sample. With the aid of this figure it is possible to calculate the original weight of the undigested material before treatment with acid. This assumes, of course, that the rock is fairly homogeneous and that it has soaked long enough so that the acid has reached the interiors of the fragments. If chert and similar materials are present, they must be reported separately. The weight of the original sample less the original weight of the undigested portion gives the actual weight of the sample used, and subsequent calculations are based on this figure.*

INTERPRETATION OF DATA

The results of the analyses of the Niagara Gorge rocks permit a more detailed interpretation of an already well known section.

The general characteristic of the formations as well as a graphic presentation of the results of the analyses, and the positions of the samples in the section are shown in Fig. 1. The data are tabulated in Table 1.

Short megascopic descriptions of Niagara Gorge specimens and also of other Irondequoit formation specimens (see Table 2 and Fig. 2) follow.

Specimens "A" through "S" are from the Niagara Gorge. The other Irondequoit specimens are from localities given.

A. Queenston formation, near middle of exposed portion of formation. Red, blocky shale, weathering to irregular fragments.
B. Queenston formation, 2 to 3 ft. beneath top. Brick red shale, similar to A.
C. Cataract formation, Whirlpool member, 4.5 ft. below top. Light gray massive sandstone.
D. Cataract formation, Manitoulin member, 13 ft. below top. Very dark gray, fissile shale.
E. Cataract formation, Cabot Head member, 29 ft. below top. Coarse, greenish gray shale.
F. Cataract formation, Cabot Head member, 14 ft. below top. Rather thin bedded, very dark red shale which is almost fissile.
G. Albion formation, Grimsby member, 10.7 ft. below top. Rather massive red and

* This method of calculation was used by Arthur S. Gale, Jr., in unpublished studies of the Menteith limestone made at the University of Rochester.

TABLE 1. *Mechanical analyses of Niagara Gorge sediments*

Specimen	Ungraded Coarse	.250–.105 mm.	.105–.050 mm.	.050–.025 mm.	.025–.010 mm.	.010–.005 mm.	.005–— mm.	Soluble[4]	Total %
S	00.38			07.57	07.80	04.68	11.75	67.82	100.00
R	01.80			08.23	09.73	04.12	10.89	65.27	100.04
Q	Present			00.82	07.16	11.69	31.58	47.92	99.17
P	00.13[1]			00.00	00.86	01.72	06.71	90.59	99.99
O	00.03[2]			00.00	00.31	00.00	01.22	98.44	100.00
N	00.23			00.11	00.00	00.11	00.65	98.88	99.98
M	00.12		00.15	00.09	00.18	00.18	01.24	98.03	99.99
L	00.11[2]			00.00	01.38	02.21	07.72	88.67	100.09
K	00.38			00.10	02.20	02.31	08.22	86.83	100.04
J	00.18[2]			01.33	04.49	02.43	08.11	83.46	100.40
I			09.94	00.25	00.13	00.25	01.48	87.96	100.01
H	35.87	35.60	18.55					45.59[3]	100.00
								01.96	
G		47.32	19.35					26.46[3]	93.13
								01.27	
F			06.91	06.36	16.33	09.80	43.80	16.81	100.01
E	10.43			06.49	09.27	12.67	48.15	13.07	100.08
D			01.02	01.75	11.20	15.16	53.74	17.94	100.81
C		51.97	07.81					35.17[3]	94.95
								02.21	99.95
B			02.49	08.55	11.08	11.42	47.94	18.55	100.01
A			00.86	00.17	15.11	14.60	40.44	28.83	100.01

[1] Includes aggregate.
[2] Includes secondary sulphides.
[3] Soluble in HF.
[4] Soluble in HCl except as noted.

TABLE 2. *Mechanical analyses of Irondequoit sediments*[1]

Specimen	Ungraded Coarse	.250–.105 mm.	.105–.050 mm.	.050–.025 mm.	.025–.010 mm.	.010–.005 mm.	.005–— mm.	Soluble	Total %
O	00.03[2]			00.00	00.31	00.00	01.22	98.44	100.00
N	00.23			00.11	00.00	00.11	00.65	98.88	99.98
M	00.12		00.15	00.09	00.18	00.18	01.24	98.03	99.99
T				00.81	05.64	13.38	55.57	24.66	100.06
U				01.96	06.88	07.04	17.82	66.39	100.09
V				00.00	00.89	00.25	01.25	97.60	99.99
W				00.27	00.27	00.00	00.77	97.96	99.27

[1] See macroscopic description of specimens for localities.
[2] Includes secondary sulphides

gray sandstone. The sample was taken from a bed two in. thick, one surface of which appeared shaly and the other was marked by structures which may have been mud flows or worm markings.

H. Albion formation, base of Thorold member. Massive gray sandstone.

I. Reynales formation, base. Crystalline limestone with black phosphatic nodules and fossils.

J. Reynales formation, 9½ ft. below top. A rather massive, silty, calcareous rock.

K. Reynales formation, 4 ft. below top. A fine grained, calcareous rock appearing to contain a large amount of silty or argillaceous materials. It is hard and compact and breaks in irregular pieces.

L. Reynales formation, top. A rather dense crystalline limestone.

M. Irondequoit formation, base. Coarsely

crystalline, buff limestone with fossils and large pebbles of Reynales type.

N. Irondequoit formation 4.8 ft. above base. Coarsely crystalline, massive, fossiliferous limestone.

O. Irondequoit formation, 3 ft. below top. Buff, coarsely crystalline, fossiliferous limestone.

P. Reef at contact of Rochester and Irondequoit formations. A very dense, fine grained, bluish, calcareous rock with which is intermingled more coarsely crystalline material and fossils.

Q. Rochester formation, near middle. Gray shale.

R. Rochester formation, 1 ft. below top. Hard gray siltstone.

S. Lockport formation, base.

T. Irondequoit formation, Second Creek, near Sodus Bay, New York. Gray shale.

U. Irondequoit formation, Second Creek, near Sodus Bay, New York. Gray shale.

V. Irondequoit formation, Oswego Quadrangle, New York, SE Ninth. Limestone.

W. Irondequoit formation, Oswego Quadrangle, New York, SW Ninth. Limestone.

The data dealing with clastic fragments greater than .005 mm. (silts and sands) have been plotted as cumulative curves (Fig. 1). The clastic fractions smaller than .005 mm. (clays) and the hydrochloric acid soluble portions are indicated by bar graphs drawn as units with the cumulative curves. The advantages of cumulative curves have been discussed by Krumbein (5) and the union of cumulative curve and bar graph gives a complete picture of a sediment, particularly when the the chemical composition of the hydrochloric acid soluble portion is included on the bar graph as has been done for three specimens in Fig. 3. The curves are plotted on a three cycle semi-logarithmic base.

The size classes used are those of the Bureau of Chemistry and Soils and are shown in Table 3.

TABLE 3. *Size classes*[1]

Diameter, mm.	Conventional name
2.0 to 1.0	Fine gravel
1.0 to 0.5	Coarse sand
0.5 to 0.25	Medium sand
0.25 to 0.10[2]	Fine sand
0.10 to 0.05	Very fine sand
0.05 to 0.025	Coarse silt
0.025 to 0.010	Medium silt
0.010 to 0.005	Fine silt
0.005	Clay

[1] Principally after the Bureau of Soils. Olmstead, L. B., Alexander, Lyle T., and Middleton, H. E., "A Pipette Method of Mechanical Analysis of Soils Based on Improved Dispersion Procedure," United States Department of Agriculture, Technical Bulletin No. 170, January 1930.

[2] 0.105 mm. used to conform to screen size.

DISCUSSION OF FORMATIONS

The sediments indicate that the environment under which the Queenston accumulated was a near sea level one. At times it was principally influenced by shallow marine waters and at others by streams with broad flood plains and gentle gradients. Shallow lakes or remnants of the sea dried and left salty muds. Silt was blown about by the wind. The red color may be assumed to have been inherited from the distributive area of the sediments; probably a warm humid region similar to the conditions in which lateritic soils are being formed today.

The curves (A and B, fig. 1) show small amounts of the finer grades of sand and an abundance of silt and clay which were brought in by the usually sluggish streams or blown in. Poor sorting may indicate variety in the agents of deposition.

Similarity of the Queenston curves to those representing the shaly facies of the Cataract is noticeable (D, E, and F, fig. 1). It is probable that an environment similar to the Queenston was recurrent during Cataract time.

The curve representing the Whirlpool member of the Cataract (C, fig. 1) is the steepest shown and indicates a well sorted sand. This together with the stratigraphic relationships indicates deposition along a beach of the incoming Silurian sea whose presence during at

least part of upper Medinan times is demonstrated by the presence of marine fossils.

The variability in the Cataract and Albion sediments reflects either isostatic unstability in the area where they were deposited or climatic changes in the area supplying the sediments, or both. Similarity of the curves representing the sediments of the Grimsby member of the Albion (G and H, fig. 1). to those of the Whirlpool is apparent, but the former are more poorly sorted.

The remaining curves are for the most part quite different and demonstrate the dominating influence of the sea. The increase in constituents soluble in hydrochloric acid is marked and the environment had probably become more stable as far as sedimentation was concerned.

The Reynales and the Irondequiot

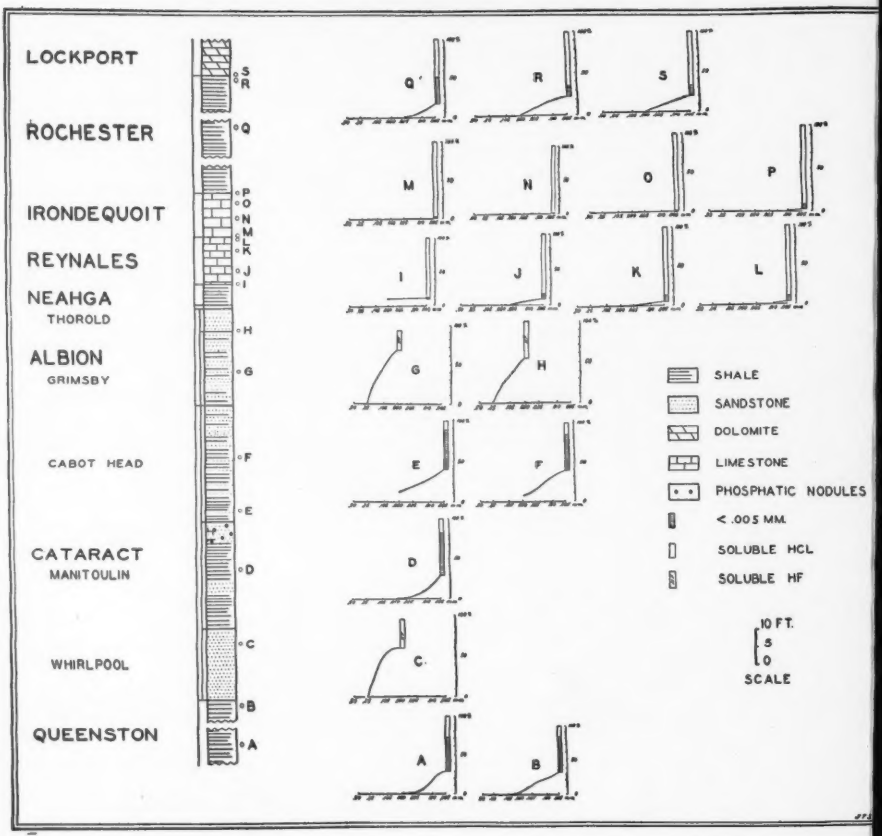

FIG. 1.—Niagara Gorge section and cumulative curves showing mechanical analyses. For explan tion see text. For information regarding the stratigraphy of the Albion and Cataract formations, I am indeb ed to Helgi Johnson, personal conversation.

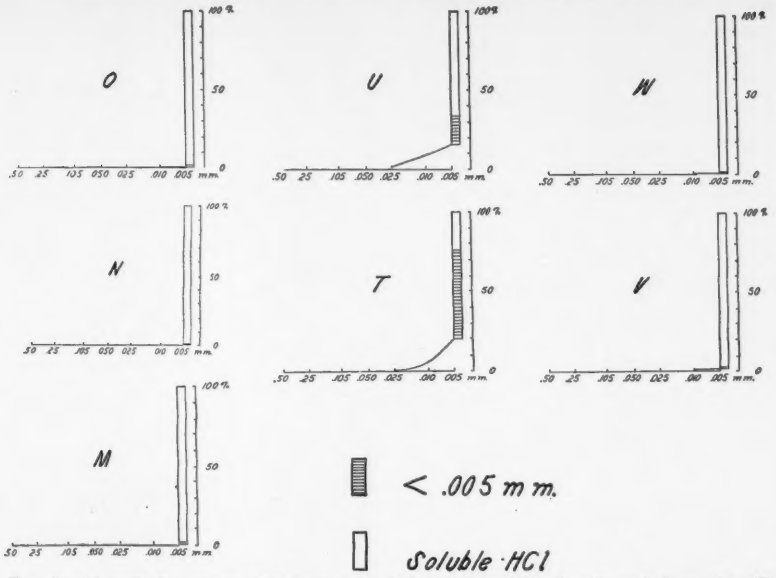

FIG. 2.—Cumulative curves showing mechanical analyses of the Irondequoit formation. For locations of specimens see text.

formations are both limestone but the rock is easily distinguishable by means of the analyses, making it possible to demonstrate the true contact of the two formations. The unconformity between the two is occupied to the east of Rochester by shales. The contact has usually been placed at a shale break near the top of the Reynales, thus correlating this shale with one of the shales at Rochester. There is a marked contact a few inches above in the overlying limestone. This contact is marked by irregularity, a change in lithology and reworked pebbles of the Reynales in the base of the Irondequiot. The analyses indicate a break in sedimentation at this point. Specimen L, taken above the shale break but below the unconformity, is similar to J and K taken farther down in the Reynales. Like them it has appreciable amounts of silt and clay, whereas M taken just above the unconformity resembles the remainder of the Irondequoit specimens N and O and has negligible amounts of these grade sizes.

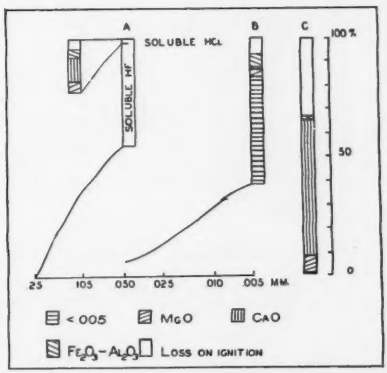

FIG. 3.—Supplemented cumulative curves showing mechanical analyses and chemical analyses of the HCl soluble portions of three specimens from the Niagara Gorge.

A. Albion formation, base of Thorold member.
B. Cataract formation, Cabot Head member.
C. Irondequoit formation.

The chemical analyses were made at the University of Rochester by Seward E. Beacom.

A specimen (specimen P, Fig. 1) from the reef at the contact of the Irondequoit and Rochester formations contains more clastic constituents than the former but less than the latter. It probably represents early Rochester time.

The presence of clays and unsorted silts in the Rochester (curves Q and R, Fig. 1) may reflect the rapid currents to the east which deposited the Herkimer sandstone. However, the calcareous silty clays indicated by the analyses do not grade directly into sands when they are traced eastward toward the source of supply as might be expected theoretically. In Rochester times the Herkimer sandstone was deposited as a shoreward facies but it graded seaward into sandy and pure limestones and these passed still farther seaward into the fine calcareous clastics which are at present represented in the Niagara area by the Rochester shale.

There is an increase in soluble constituents at the top of the Rochester, principally at the expense of the clays. The environment at the time these sediments were deposited was becoming more like that under which the calcareous Gasport member of the Lockport formation was laid down.

The one analysis of the lockport made from a specimen taken at the base shows no essential difference from the upper Rochester. To the east at Rochester, New York, the Lockport becomes very sandy in places.

Figure 2 (Table 2) shows a series of curves drawn from analyses of the Irondequoit made from samples from several localities. T and U from the Sodus area are unlike the others but they represent the shale facies which is not present at Niagara. They do show the importance of calcareous materials in the Irondequoit, even in the clastic phases. V and W from near Oswego are remarkably like M, N, and O from the Niagara Gorge. There is a slight increase in the clastic portions in the Oswego area but this characteristic might be expected to be even more marked this far to the east.

DISCUSSION OF THIN SECTION METHOD

The thin section and mechanical techniques are considered supplements rather than alternatives. Each has its limitations. Thin sections offer an opportunity to examine, but a small portion of the specimen and grain sizes are frequently not maxima; on the other hand the technique used here does not permit a study of the relationships of the various constituents or the physical character of the hydrochloric acid soluble minerals. Mineralogical studies can be made of the fractions separated by the mechanical method although this was not done in the present case.

In Fig. 2 of his paper Alling (1) has shown graphically a quantitative study of the Niagara Gorge rocks based on thin sections. These results, when compared with those of the present paper, raise some questions regarding both methods. Alling's results are not presented in quite the same units as those of the writer's and a certain amount of interpolation is necessary in making comparisons. Alling's carbonates correspond roughly to my soluble constituents although in the cases of the Queenston and the middle Rochester the hydrochloric acid soluble constituents are greater than the microscopically determined carbonates. It seems plausible to expect that some of the clays would go into solution and that very fine carbonates disseminated through the clays might not be measured microscopically. Perhaps the correct figures lie somewhere between these shown by our results. In the case of the upper Rochester the microscope showed a greater amount of carbonates than was arrived at by loss through solution in hydrochloric acid and this seems difficult to explain except by chance in the choice of material for a thin section.

The results of both methods suggest the fluctuating conditions under which the beds between the Queenston and the Clinton were probably deposited. The data from the two types of analyses compare very favorably in the cases of

the calcareous Reynales and Irondequoit formations.

Alling's (1) Fig. 3, in which he shows graphically the results of measurements of quartz grains, presents a series of curves which seem too complicated to be natural. He states that less irregular curves would have resulted from a greater number of measurements but this factor alone does not seem adequate to explain the preponderance of double and multiple peaked curves. The peaks of the double peaked curves are frequently close together. The measurements made were diameters of circles with areas equal to the areas of the various grains.

It would be possible to obtain double peaked curves similar to these if all of the grains were of the same approximate size, slightly oblong, and not orientated. Lath shaped grains would probably be oriented but nearly equidimensional grains might not be. Those sectioned parallel to the longest dimensions would be responsible for one peak and those sectioned parallel to the shorter dimensions would be represented in the other peak of the curve. If more than one grade size was present this result would be repeated and a multiple peaked curve would result.

CONCLUSIONS

Mechanical analyses of the Niagara Gorge sediments yield results which are characteristic of the formations which they represent and which can be duplicated. These are more useful when supplemented by chemical analyses of the hydrochloric acid soluble portions of the samples.

The section studied shows the stages of transition from mud flat to marine condition. Fluctuation in the character of the sediments may reflect climatic changes in the areas from which they were derived as well as isostatic shifts in the region of deposition.

REFERENCES

1. ALLING, H. L., *1936*, Petrology of the Niagara Gorge sediments, *Rochester Acad. Sci., Proc.*, vol. 7, 189–207.
2. POSTEL, A., *1933*, Preparation of clay samples for elutriation by steam agitation, *J. Sed. Pet.*, vol. 3, 119–120.
3. TAYLOR, G. L. and GEORGESEN, N. C., *1933*, Disaggregation of clastic rocks by use of a pressure chamber, *J. Sed. Pet.*, vol. 3, 40–43.
4. OLMSTEAD, L. B., ALEXANDER, L. T., and MIDDLETON, H. E., *1930*, A pipette method of mechanical analysis based on improved dispersion procedure, *United States Dept. Agr. Tech. Bull.*, No. 170.
   KRUMBEIN, W. C., *1932*, The mechanical analysis of fine-grained sediments, *J. Sed. Pet.*, vol. 2, 140–149.
   ———, *1933*, The dispersion of the fine-grained sediments for mechanical analysis, *J. Sed. Pet.*, vol. 3, 121–135.
5. ———, *1934*, Size frequency distributions of sediments, *J. Sed. Pet.*, vol. 4, 69.

JOURNAL OF SEDIMENTARY PETROLOGY, VOL. 9, NO. 2, PP. 86–91, FIGS. 1–8, AUGUST, 1939

REFLECTION OF PROVENANCE IN HEAVY MINERALS OF JAMES RIVER, VIRGINIA[1]

MARCELLUS H. STOW
Washington and Lee University, Lexington, Virginia

ABSTRACT

A study of samples of sand collected from the James river of Virginia between Clifton Forge, Alleghany County, and Smithfield, Isle of Wight County, shows a distinct correlation between stream sediments and country rock of the adjacent drainage area. There is a marked difference in the mineral content of the sands derived from the rocks of the four principal physiographic provinces—*viz.*, the sedimentary rocks of the Valley and Ridge, the igneous rocks of the Blue Ridge, the metamorphic rocks of the Piedmont, and the sedimentary rocks of the Coastal Plain.

INTRODUCTION

In 1929 samples of sand were collected along the James river from Goshen Pass, Rockbridge County, on the North Branch and Clifton Forge, Alleghany County, on the main James, to Lynchburg, Campbell County. The results of this study were published in 1930. In more recent years collecting was continued down the river to Smithfield, Isle of Wight County, near its confluence with Chesapeake Bay. In this distance of over 200 miles the James traverses the five physiographic provinces of Virginia, namely, Valley Ridges, Great Valley, Blue Ridge, Piedmont, and Coastal Plain. For present purposes the first two are considered together as the Valley and Ridge Province (Fig. 1).

GENERAL GEOLOGY

Reference to the geologic map of Virginia (2) will show that in the area drained by the James River the Valley and Ridge Province consists of Paleozoic sandstones, shales, and limestones, the Blue Ridge of granites, hypersthene granodiorites, and some gneisses, the Piedmont of slates, schists, gneisses, and marbles, and the Coastal Plain of Tertiary and Cretaceous sands and clays.

[1] Read before Section E, A.A.A.S., Richmond, Virginia, December 28, 1938.

Abstract: Sands of the James River, G.S.A., Bull., vol. 49, no. 12, Pt. 2, p. 1962, December 1938.

FIELD AND LABORATORY PROCEDURE

Specimens were collected from the shore of the James river at normal water level and a few hundred feet below the mouth of various tributary streams. A compound sample was obtained by taking several small quantities of sand that appeared to represent the general deposit of the area. In the laboratory clay and fine material were removed by agitating the sample in water and decanting the suspended matter (3). Concentration of the heavy minerals was accomplished in bromoform (Sp. G. =2.87) by the standard procedure of sedimentary petrography. A detailed quantitative study was not made, hence relative frequencies were obtained by visual estimation and were expressed in terms of *Flood*, *Abundant*, *Common*, and *Rare*.

HEAVY MINERALS

In the samples of stream sand from the Valley and Ridge Paleozoics, limonite is the predominant heavy mineral. In the western part of this province, limonite represents as high as 95 per cent of the heavy mineral separate (fig. 2). This high percentage is doubtless due to the fact that the James drains large areas of limonite iron ore to the west. The amount

of limonite decreases progressively eastward, but still represents about 80 per cent of the heavy minerals in the sand of the river where it enters the water gap in the Blue Ridge Mountains at Balcony Falls. Ilmenite is the next most abundant mineral. The only non-opaque heavy minerals are zircon and tourmaline with an occasional grain of rutile.

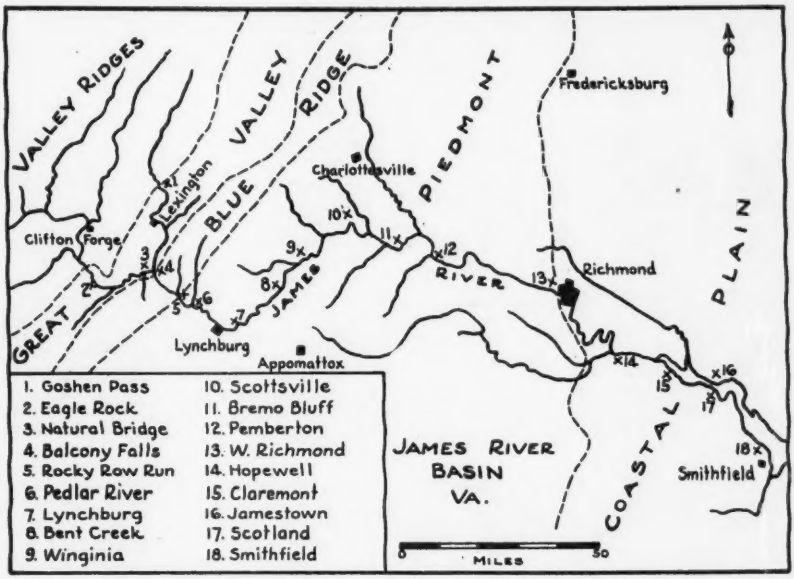

FIG. 1

The first sample that gave any indication of detritus derived from other than sedimentary rocks was a sample from the mouth of Arnolds creek (Fig. 1, locality 3). The headwaters of this stream are in the Lovingston granite-gneiss of the Blue Ridge Province. A few grains of amphibole and epidote were found in this sample, but the main composition was that of the Valley and Ridge sediment.

At Balcony Falls (Fig. 1, locality 4) where the James enters the water gap at the western side of the Blue Ridge mountains, the drainage has been preponderantly from the Paleozoic sedimentary formations, but Arnolds creek, draining crystalline rocks, has entered the main stream and hence the sand at Balcony Falls contains amphiboles and epidote in addition to those minerals characteristic of the Valley and Ridge Province (Fig. 3).

At the mouth of Rocky Row Run (fig. 1, locality 5) at the eastern end of the water gap, the sand contains a smaller amount of limonite; but ilmenite, tourmaline, zircon, rutile, amphibole, epidote, leucoxene, garnet, and muscovite are present in small amounts. As is indicated by this suite of minerals, Rocky Row Run drains a large area of crystalline rocks, the Lovingston granite-gneiss particularly, and the sand of the James below the mouth of this stream reflects this change in source of supply.

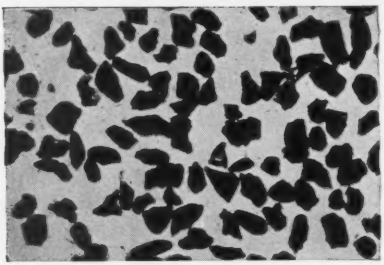

FIG. 2.—Heavy mineral separate from James River at Eagle Rock, Botetourt Co., Virginia. ×15.

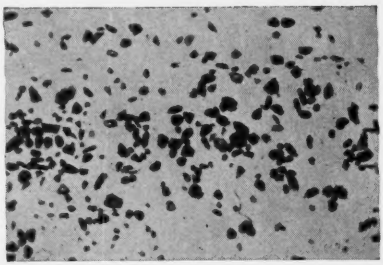

FIG. 3.—Heavy mineral separate from James River at Balcony Falls, Rockbridge Co., Virginia. ×15.

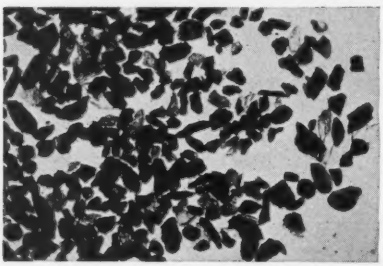

FIG. 4.—Heavy mineral separate from James River at Lynchburg, Campbell Co., Virginia. ×15.

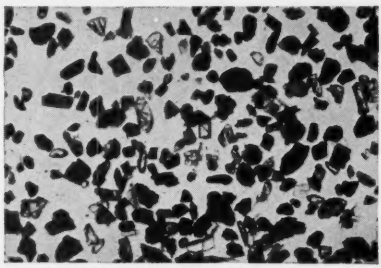

FIG. 5.—Heavy mineral separate from James River at Wingina, Nelson Co., Virginia. ×15.

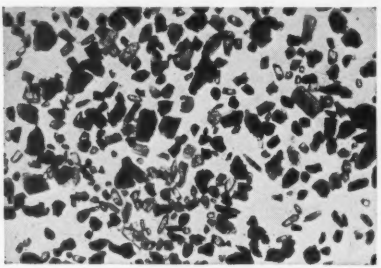

FIG. 6.—Heavy mineral separate from James River at Bremo Bluff, Fluvanna Co., Virginia. ×15.

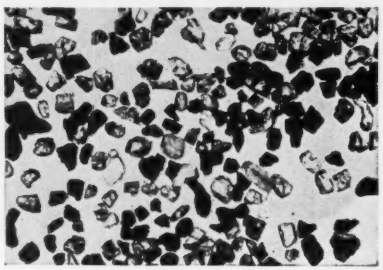

FIG. 7.—Heavy mineral separate from James River at Hopewell, Prince George Co., Virginia. ×15.

A few miles below Rocky Row Run, Pedlar river (Fig. 1, locality 6) enters the James after pursuing a course through extensive areas of the Lovingston granite-gneiss and other crystallines. Minerals contributed to the main stream by this tributary are essentially the same as those contributed by Rocky Row Run.

The first sample from the James river after it has entered the Piedmont Province was from Mt. Athos at the east side of Lynchburg (Fig. 1, locality 7). The river has crossed a few miles of Wissahickon schist and has received sediment from a few small tributaries draining this area and from some areas of soapstone, serpentine, and other metamorphic rocks. The sand from Lynchburg contains an abundance of chlorite, muscovite, and ilmenite, and appreciable amounts of hornblende, epidote, garnet, and small amounts of leucoxene, kyanite, staurolite, and zircon. It should be noticed that although the main stream has received very little detritus from these metamorphic rocks, nevertheless the change from an igneous rock source to one of metamorphic rocks is recorded in the appearance of chlorite in great abundance and staurolite and kyanite in small amounts (Fig. 4).

Continuing donwstream, the next sample examined was from below the mouth of Bent creek (Fig. 1, locality 8). By the time the river reaches this locality it has traversed a considerable distance on the Piedmont and has received drainage and sediment from areas of the Wissahickon schist, Catoctin greenstone, Cockeysville marble, and greenstone volcanics. In this sample of sand the following minerals were found, in order of decreasing frequency: hornblende, muscovite, kyanite, staurolite, zircon, chlorite, epidote, garnet, hypersthene, tourmaline, rutile, sillimanite, sphene, and actinolite. The variety of minerals present indicates the variety of rock types from which the sediment has been derived.

Farther downstream, at Wingina (Fig. 1, locality 9), the sample contained essentially the same minerals as found at Bent creek, plus an occasional grain of apatite, diopside, and monazite (Fig. 5). These three are present in such small amounts that it is probable that they were present in the Bent creek area but were not included in the sample. Drainage sources here are the same as at the preceding locality. At Scottsville (Fig. 1, locality 10) drainage from an area of Triassic rocks of the Newark series has been added to the river, but apparently has contributed no new minerals to the list of those already found at Bent creek and Wingina. At Bremo Bluff (Fig. 1, locality 11) sources of sediment are the same as at previous localities, with the exception of the addition of an area of Peters Creek quartzite. The mineral assemblage here remains unchanged (Fig. 6). Samples were obtained from Columbia, Cartersville, Pemberton (Fig. 1, locality 12), Goochland, and West Richmond (Fig. 1, locality 13). In all of these samples the heavy mineral assemblages were essentially similar and did not differ from those described from Wingina, with the exception of zoisite, which was found occasionally.

A sample collected at Hopewell (Fig. 1, locality 14), below the mouth of the Appomattox river is characteristic of sediment from the James river after it reaches the Coastal Plain Province. This sand contained an abundance of kyanite. Kyanite had been found in all of the sands from the Piedmont, but its relative frequency was "Rare." At Hopewell, kyanite is very common. The reason for this increase in proportion is evident if the geologic map of Virginia is consulted. It will be seen that the Appomattox river heads near the town of that name and flows eastward through the areas of Wissahickon schist which contains large masses of kyanite-bearing quartizites. Staurolite and sillimanite likewise are present in some abundance in this area drained by the Appomattox river. The localization of these three minerals in the crystalline rocks of this area is reflected in the increased amount in the sands of the James river below the mouth of the Appomattox. Other minerals present in the Hopewell sample are ilmenite, hornblende, epidote, in large amounts; and rutile, sphene, tourmaline, and zircon, in small amounts (Fig. 7). Other samples from the Coastal Plain Province were from Claremont, Jamestown, Scotland,

and Smithfield (Fig. 1, localities 15, 16, 17, 18). These samples showed essentially the same minerals and characteristics as the one from Hopewell.

SUMMARY

Sand from the Valley and Ridge Province contains a maximum of five heavy minerals. They are limonite, ilmenite, zircon, tourmaline, and rutile.

Sand from the Blue Ridge Province contains a maximum of twelve heavy minerals. They are ilmenite, limonite, leucoxene, muscovite, chlorite, garnet, hornblende, hypersthene, epidote, tourmaline, zircon, and rutile.

Sand from the Piedmont Province contains the greatest variety of minerals of the four provinces under discussion. Twenty-four different minerals were identified, with as high as 16 in a single sample. They are zircon, hornblende, limonite, ilmenite, tourmaline, rutile, leucoxene, epidote, garnet, muscovite, chlorite, hypersthene, staurolite, andalusite, kyanite, sillimanite, sphene, actinolite, apatite, biotite, diopside, monazite, tremolite, and zoisite(?).

Sand from the Coastal Plain Province contains 16 different minerals with as many as thirteen in a single sample. They are ilmenite, zircon, tourmaline, rutile, leucoxene, hornblende, epidote, garnet, muscovite, chlorite, hypersthene, staurolite, andalusite, kyanite, sillimanite, sphene, actinolite, apatite, biotite, diopside, monazite, tremolite, and zoisite(?).

HEAVY MINERALS OF JAMES RIVER SANDS

Minerals	Physiographic Provinces			
	Valley & Ridge	Blue Ridge	Piedmont	Coastal Plain
Limonite	F	A	C	
Ilmenite & Magnetite	C	C	C	A
Zircon	R	R	A	C
Tourmaline	R	R	R	R
Rutile	R	R	R	R
Leucoxene		C	C	R
Hornblende		R	A	C
Epidote		R	C	C
Garnet		R	R	C
Muscovite		C	C	R
Chlorite		C	C	R
Hypersthene		R	R	R
Staurolite			R	C
Andalusite			R	R
Kyanite			R	C
Sillimanite			R	C
Sphene			R	R
Actinolite			R	
Apatite			R	
Biotite			R	
Diopside			R	
Monazite			R	
Tremolite			R	
Zoisite?			R	

F = Flood, A = Abundant, C = Common, R = Rare

FIG. 8

CONCLUSIONS

From Fig. 8 it will be seen that not only does the variety of minerals in the sands change from province to province, but also the relative amounts of each variety. In the Valley and Ridge Province the limonite is in "Flood" propor-

tions; this amount decreases to "Abundant" in the Blue Ridge, to "Common" in the Piedmont and is absent from sediment collected from the river of the Coastal Plain. On the other hand the relative amounts of ilmenite and zircon increase as the stream flows from Valley and Ridge to Coastal Plain. The relative amounts of tourmaline and rutile remain about constant. Leucoxene is "Common" in the Blue Ridge and Piedmont sands but is "Rare" in the Coastal Plain. Hornblende, which is "Rare" in the Blue Ridge, is increased to "Abundant" in the Piedmont, and reduced to "Common" in the Coastal Plain. Epidote increases from "Rare" to "Common" in the Blue Ridge, Piedmont, and Coastal Plain, respectively, garnet from "Rare," in the Blue Ridge and Piedmont to "Common" in the Coastal Plain. Muscovite and chlorite are "Common" in the Blue Ridge and Piedmont, but are reduced to "Rare" in the Coastal Plain. Hypersthene remains "Rare" throughout the three provinces.

Comparing the minerals that are common to both the Piedmont and Coastal Plain it will be seen that staurolite, kyanite, and sillimanite increase in relative amounts from "Rare" in the former to "Common" in the latter province, and that andalusite and sphene remain "Rare" in both provinces. The remaining seven minerals in the table (fig. 9), actinolite, apatite, biotite, diopside, monazite, tremolite, and zoisite(?), were observed in an occasional sample from the Piedmont.

In the Coastal Plain Province, the James river flows in a drowned valley, hence is considerably wider than at any part up stream. Wave action in this wider area has been an effective destructive agent of such minerals as muscovite, chlorite, actinolite, apatite, biotite, diopside, tremolite, These have been either completely destroyed or winnowed down to rare occurrence. Hence by destruction and sorting the proportions of the more stable minerals have been increased. Examples are ilmenite, garnet, staurolite, kyanite, and sillimanite. This is in addition to mere increase in amount due to increase in material supplied.

From the foregoing it is evident that distinct differences in heavy mineral composition exist between sediments from the various physiographic provinces of the James river basin. In this region each physiographic province is represented by distinctly different rock types, hence the change in mineral composition of the sands is a direct reflection of the change in rock types and an indirect reflection of change in physiographic province.

Much detailed work remains to be done on the problem. As yet very little attempt has been made in this region to trace specific minerals to a source in a specific formation or rock type. A study of the accessory minerals of the various rocks of these provinces should be made, with the method of procedure following that of sedimentary petrology rather than of the thin-section. Elaboration of this procedure under auspicious circumstances might throw some light on the location and development of ancient physiographic provinces.

REFERENCES

1. Stow, M. H., *1930*, A preliminary investigation of some sediments from James river, Virginia; *Am. Mineralogist*, vol. 15, 528–533.
2. Geologic map of Virginia; Va. Geol. Survey, *1928*.
3. Stow, M. H., *1932*, Washing grains to obtain most desirable size of grains for microscopic study; *Am. Mineralogist*, vol. 16, 226.
4. Johnson, J. H., *1935*, Heavy minerals from some Paleozoic formations, *Virginia Acad. Sci. Proc.*, (*Abst.*) 68.
5. ———, *1936*, *1937*, Heavy minerals in Silurian and Devonian sandstones, *Virginia Acad. Sci. Proc.* (*Abst.*), 71.
6. Smith, J. H., *1936*, Insoluble residues in some Ordovician limestones near Lexington, Virginia, *Virginia Acad. Sci. Proc.* (*Abst.*), 70.

Ergebnisse der sedimentpetrologischen Forschung in den Niederlanden und den angrenzenden Gebieten 1932–1937, by Edelman, C. H., Geologische Rundschau, 29, Heft 3/5, 223–271.

The reviewer believes that this is one of the most important heavy mineral papers published in recent years because it summarizes the work of one of the most active schools of sedimentary petrography,—that of Edelman and his coworkers at Wageningen. The summary is especially valuable since a large proportion of the literature cited is in Dutch, and to date, only one paper on Holland and adjoining areas has been written in English. Edelman summarizes or mentions the work contained in 52 papers. Of these, 18 bear directly on the subject of the paper under review. Included in the 17 of these published up to the present, eight are in Dutch (320 pages), six in German (73 pages), two in English (160 pages), and one in French (15 pages).

Since the paper under review is itself a summary of at least 18 other papers, any further condensation is difficult. However, a few important points should be mentioned:

1. The work is essentially *regional* in character. Previously, little was known about the stratigraphy of the Tertiary and Quaternary sediments of Holland. Collections were made all over the country, mostly from borings. Stratigraphic relations were worked out from heavy minerals.

2. It is possible to delimit a number of sedimentary-petrologic provinces in Holland. (A "sedimentary-petrologic province" is defined as "the totality of sediments which form a natural unit by virtue of their distribution, their age, and their origin," or as "a definite association of detrital minerals in space and time.") Thus, the Rhein sediments since Tertiary time have been consistently characterized by the presence of saussurite, and their horizontal and vertical limits can be traced by it. Together these sediments make up a sedimentary-petrologic province. There are several other provinces. Often there is mixing of material from more than one province, but this mixing does not obscure the courses of the old drainage systems, nor does it preclude an unraveling of the local Tertiary and Quaternary history.

3. The mineral suites ("Mineralassoziationen") of the various provinces are so distinct from one another that qualitative methods are sufficient to differentiate them. For example, the Rhein sediments, as said before, contain saussurite, those of the Maas (Meuse) rutile, staurolite, and kyanite, and those from the north garnet, epidote, and hornblende. One need not worry about varietal characters, nor about numerical comparisons (though quantitative data on mineral frequencies are always given).

A number of interesting sidelights emerge from the work, only a few of which can be mentioned: a. The North Sea and the English Channel are excellent places for the interpretation of physiographic and geologic history by heavy minerals (see Baak, reviewed in this Journal, 6, 1936, 121); b. wear and chemical change of heavy minerals is inconsiderable during any one cycle, so that the change in composition along the present Rhein, for example, would be largely a function of addition of new species, not destruction of ones already present; and c. a great deal can be told about the time of uplift of the Ardenne and Rhenishschiefergebirge areas by the concomitant changes in heavy minerals carried by the Maas and Rhein, respectively.

This paper is not only a very important, but a most encouraging one. In a great many instances, heavy minerals seem to yield but little information, and it is often said that they lack value, and that they are unreliable. To those who are discouraged, as well as to the skeptics, a careful reading of this paper is recommended.

LINCOLN DRYDEN

Bryn Mawr College
Bryn Mawr, Pa.